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THE APPLICATION OF THE X-RAY IMAGE INTENSIFIER

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For many years electronics has been engaged in the problems of amplifying very weak currents and voltages. In recent years, partly owing to the stimulus of television, a new branch of electronics, that is, the intensification of light, has emerged. The original object of this development was the conversion of long-wave, into short-wave light ("wavelength-transformation") which was investigated in the Philips laboratories at Eindhoven as long ago as 1934. Now, however, the emphasis is on luminance intensification with special reference to the intensification of weak fluorescent images.

The first article on the X-ray image intensifier to appear in this Review was published in 1952; since then, laboratory experiments and practical tests have produced much new and interesting information concerning this intensifier, and it is now considered worth while to publish one or two articles describing these developments. The main points considered here are: the minimum size of detail perceptible with the image intensifier; the optical problems involved; photography and cinematography with the image intensifier.

The present articles refer mainly to the existing type of image intensifier. Little is said as to the probable future trend of development in image intensification; this does not imply, however, that the present results are considered the last word in this field. On the contrary, we should emphasise that the subject is still developing and we hope to report further progress in due course.

I. GENERAL SURVEY

by M. C. TEVES. 621.386.8:616-073.75:621.383.8

By way of introduction, the purpose, principle and design of the X-ray image intensifier at present in regular production [1]) will be briefly re-stated.

The purpose of the image intensifier is to enable as much information as possible to be extracted from the fluorescent image of the particular object, for a given X-ray dose. The theoretical and practical factors governing the amount of information obtainable from the image are discussed fully in the second article of this series. It can be shown from these considerations that with ordinary fluoroscopy, the information in the screen depends on the X-radiation absorbed by the screen. The amount of radiation absorbed is closely related the dose to which the patient is exposed. However, the observer cannot extract all this information, owing to the weakness of the optical link between the fluorescent screen and the human detecting organ (that is, the retina of the observer's eye). The same applies to fluorography (miniature radiography), which likewise involves

1) M. C. Teves and T. Tol, Electronic intensification of fluoroscopic images, Philips tech. Rev. 14, 33-43, 1952/53.

an appreciable loss of light in an optical link, viz. that between the fluorescent screen and the film; the loss is so great, that only about 1% of the information latent in the screen is transmitted to the film.

Full-size radiography is very much better in this respect. The direct optical contact between fluorescent screen and film here prevents any loss of light. With regard to the first two methods referred to, an image intensifier tube considerably increases the amount of information obtainable with a given dose. Compared with full-size radiography, however, it offers only secondary advantages, namely that it enables the dose to be reduced. It has the further advantage that it enables cinematography to be employed.

Hence the main purpose of the image intensifier is to make good the light loss in the optical link between the fluorescent screen and the light detector (retina of the eye, photographic film or plate, or, possibly, the photo-cathode of a television camera tube).

Description of the image intensifier

The image intensifier is an evacuated glass tube containing a fluorescent screen on a thin aluminium base (*fig. 1*); in contact with the screen is a photo-cathode. X-radiation striking the screen makes it

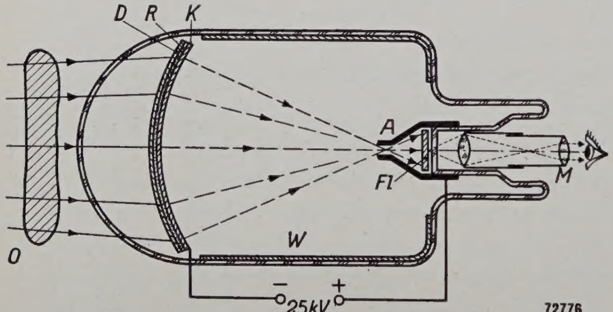

Fig. 1. Schematic cross-section of the image intensifier tube. R fluorescent screen receiving the X-radiation after it passes through the object O and the glass wall of the tube; D support carrying the fluorescent screen and the photo-cathode K. The fluorescence generated in R releases electrons from the photo-cathode. The "electron image" is reproduced, reduced in size, on the viewing screen Fl by the electric field between K and the hollow anode A. It is then observed through a simple microscope M. W is a conductive coating on the inside of the tube.

fluoresce and the light then releases electrons from the photo-cathode. The number of electrons so released from each point on the cathode is proportional to the luminous intensity of the fluorescent screen at that point. By means of an electric field, the electron image thus formed is reproduced, reduced 9 times in size, on another fluorescent screen, the viewing screen. Part of the energy of the electrons striking this screen is re-converted into fluorescent light to form a 9 times smaller facsimile of the image on the first fluorescent screen. This facsimile is then viewed through a simple eyepiece of roughly 9 × magnification, so that the image is seen in its original size, that is, roughly 13 cm in diameter, and upright, but about 1000 times brighter than before.

The luminance intensification arises from two factors (which, however, are not independent of each other). Firstly, an increase in the overall luminous flux (or "lumen intensification") due to the fact that the electrons from the photo-cathode are accelerated by the electric field: there is an accelerating voltage of roughly 25 kilovolts between the photo-cathode and the viewing screen. The higher the energies of the electrons striking the viewing screen, the more intense the fluorescence produced. Although only about 1 in every 10 light quanta falling on the first fluorescent screen releases an electron, and only about one tenth of the electron energy is converted into light on the viewing screen, the energy imparted to the electrons nevertheless results in the latter screen producing between 10 and 15 times as much luminous flux as an ordinary fluorescent screen viewing the same subject.

The second factor is the electron-optical reduction of the image size; it enables all the photo-electrons to contribute to the formation of the image, so that the amount of light generated does not depend upon the area over which these electrons are distributed. By employing a reduction of 9 times, we reduce the area within which the electron energy is concentrated by a factor of 9^2; hence the total luminous flux is emitted from an area about 80 times smaller than it would be with reproduction on a scale of 1 : 1. This, by definition, means an increase in luminance by a factor of 80. The total luminance intensification is the product of the lumen intensification and the gain from the reduction of the image size; with the tube under consideration, it is between 10 and 15 times 9^2, or from 800 to 1200. Thus the luminance is so increased as to make good all the light loss involved in the forming of the image.

In the conversion of a low-luminance image into a high-luminance one, special precautions are necessary to avoid loss of contrast or definition in the image owing to imperfections in the apparatus.

With the present image intensifier, sharpness is limited mainly by the thickness of the first fluorescent screen. However, it is also affected to some extent by the viewing screen. Blurring in the electron-

optical image forming system is almost negligible.

In principle, subtle contrasts in the low-luminance initial fluorescent image are not affected by the light-transformation (the γ of the image intensifier is unity). In practice, however, there is a slight, but unavoidable loss of contrast owing to "fogging", that is, a luminance contribution distributed more or less uniformly over the whole image. On the other hand, the increase in contrast sensitivity of the eye with increasing luminance far outweighs this slight loss. In photography, it can be made good by employing a film with a higher γ.

Although it is essential that the properties and possibilities of the image intensifier be fully investigated in the laboratory by means of "phantom tests" (see article II), its merits from the medical point of view can be determined only in actual medical practice. Such practical tests are being carried out in a number of places, e.g. in the Philips Health Centre at Eindhoven under Professor Burger and Dr. Feddema [2]), and in Maastricht by Dr. van der Plaats [3]).

Without particularizing unduly, we may quote the following examples of the usefulness of the image intensifier from these investigations (see article V).

In chest fluoroscopy, the intensifier gives good results with only one tenth of the normal X-ray dose. Apart from the fact that the resolution is at least as good under these conditions as in the direct image, the image intensifier enables the subject to be examined in a moderately lit room and without any preliminary adaptation of the eyes.

The intensifier is eminently suited for locating foreign bodies (e.g. metal particles), and for the routine examination of the setting of bone fractures.

For the examination of an oesophagus, stomach or colon into which contrast medium has been introduced, the investigation is considerably facilitated by the image intensifier.

An important use of the image intensifier is as an aid to visual positioning before the taking of an ordinary, full-size radiograph (spot film technique).

Medical experience has shown that in fluoroscopy, better results are obtained with, than without the image intensifier, especially in circumstances where the relatively small size of the field, i.e. 13 cm in diameter, is not a handicap.

As applied to fluorography, that is, photography of the viewing screen of the intensifier on film with a camera, the medical uses of the intensifier may be divided into two categories:

1) The taking of still photographs, singly or in series.
2) X-ray cinematography.

A great deal of information concerning both these uses has already been collected. It is found that the quality of a photograph taken with the image intensifier on fine-grain 35 mm film is very much the same as that of an ordinary full-size radiograph, although, with a suitable optical system, the X-ray dose required per photograph is a factor of 2-3 smaller than in full-size radiography. With regard to X-ray cinematography, it is enough to say that even with quite a long film, the X-ray dose is not heavy enough to endanger the patient; hence photographic X-ray examination can now be employed in physiological, as well as anatomical studies.

Briefly, then, we may safely say that the present image intensifier has demonstrated its value in many medical applications. However, it is still far from perfect. One of the practical improvements still required from the medical point of view is a larger image field. Moreover, the methods of presenting the image to the observer also require attention; this is important not only in fluoroscopy, but also from the point of view of cinematography. Another problem is how best to convey all the information in the film strip to the observer.

Finally, it should be pointed out that the image intensifier is also useful in industrial radiography. The relatively brighter image produced permits the visual examination of much thicker objects than has been possible hitherto. One or two examples are given in article VI.

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[2]) J. Feddema, Image intensification. Some possible diagnostic applications in cineradiography, Brit. J. Radiology **28**, 217-220, 1955.

[3]) G. J. van der Plaats, De röntgendoorlichting in verband met nieuwe ervaringen met de beeldversterker, Ned. T. Geneesk. **97**, 1056-1063, 1953.

II. THE PERCEPTION OF SMALL OBJECT-DETAIL

by T. TOL and W. J. OOSTERKAMP. 621.386.8:616-073.75:621.383.8

In X-ray diagnosis, the principal aim is to obtain the desired information concerning the organ examined, with the smallest practicable X-ray dose to the patient. In general, direct visual examination of the fluorescent image involves a very much larger dose to the patient than the taking

of a single radiograph: in fluoroscopy the radiologist requires a certain amount of time to examine all the details of the image properly, whereas in radiography the time during which the patient is irradiated, is relatively short, and the radiologist has ample opportunity to study the film when once it is developed. On the other hand, a radiograph provides the radiologist with only one instantaneous picture and therefore tells him nothing about the condition of the particular organ at different moments; such information is important when moving organs or an unrepeated effect, say, the injection of contrast medium, are to be observed. Accordingly the relatively larger X-ray doses associated with fluoroscopy give, in general, more information. Both methods, the visual and the photographic, are still in use in X-ray diagnosis; they are complementary. We shall now consider in how far the two can be improved by employing an image intensifier; this involves investigating both theoretically and practically the minimum limits of contrast and detail that can be observed for a given dose in fluoroscopy and radiography, with and without the image intensifier.

Theoretical limit of detail perception

As stated in an earlier article [1]), the perception of small object-detail is limited, according to Rose [2]) and Sturm and Morgan [3]), by the fluctuations or noise in the number of quanta involved in the observation of the particular object-detail. In fluoroscopy, for example, such detail cannot be resolved unless the difference in luminance between it and the surroundings exceeds the natural luminance fluctuation. With a radiograph, a similar argument holds good for the local fluctuations in photographic density owing to the finite size and varying concentration of the silver grains in the picture.

The magnitude of the resultant fluctuations is governed mainly by the particular stage of the image transmission at which the average number of quanta or particles, $\overline{N}$, is smallest ($\overline{N}_{\min}$). The standard deviation of the actual values of $N_{\min}$ is $\sqrt{\overline{N}_{\min}}$. The contrast between two zones of different luminance, I_1 and I_2, may be defined as:

$$C = \frac{I_1 - I_2}{I_1}.$$

The fluctuations in luminance produce contrasts determined by $I_1 \propto \overline{N}_{\min}$ and $I_2 \propto \overline{N}_{\min} - \sqrt{\overline{N}_{\min}}$; hence $C_{\text{fluct}} = 1/\sqrt{\overline{N}_{\min}}$. The minimum contrast clearly perceptible despite these fluctuations is therefore $C_{\min} = k/\sqrt{\overline{N}_{\min}}$, where k is greater than unity; it will be shown from the experimental results that the actual value of k is roughly 3. Given $\overline{N}_{\min}$, then, it is possible to calculate this minimum contrast, and also, since $\overline{N}$ is proportional to the area of the detail observed, the minimum perceptible contrast as a function of the detail diameter (d). Here we have, then, a theoretical, quantitative limit on the detail perception. If $C_{\min}$ is plotted against d on logarithmic co-ordinates the resulting curves are straight lines.

Numbers of quanta involved in the different stages of image transmission

The numbers of quanta involved in the different image-stages in fluoroscopy with, and without the image intensifier are shown diagrammatically in *fig. 1*. The integration time of the eye, that is, the time during which the eye is able to co-ordinate a certain number of light quanta into a single light-impression, is assumed to be 0.2 sec. [2])

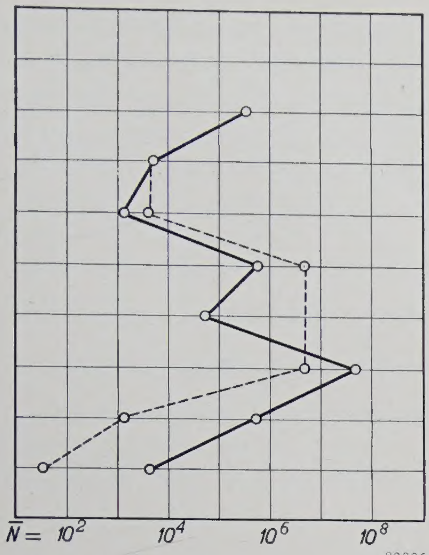
In fluoroscopy without the image intensifier, only a very small fraction (roughly 0.02%) of the light from the screen enters the pupil of the eye. In the complete image transmission chain, then, it is at the retina that the number of quanta per image-element is smallest; the screen must absorb 100 X-ray quanta to produce one effective light quantum on the retina. Hence the perception of detail is fundamentally limited by the relative fluctuations in the number of quanta effectively absorbed by the retina.

In fluoroscopy with the image intensifier, however, the number of light quanta is so increased by the 1000 times luminance intensification, as to exceed the number of X-ray quanta absorbed; here, then, perception of detail is limited by the number of absorbed X-ray quanta.

The smallest numbers of quanta are then a factor of 40 larger, and the relative fluctuations a factor of $\sqrt{40} \approx 6\times$ smaller than in fluoroscopy without the image intensifier; the theoretical minimum perceptible contrast (for a given detail size) is therefore likewise smaller by a factor of 6.

If the fluctuations in the number of X-ray quanta could be neglected, the factor by which the minimum perceptible contrast is reduced by the $1000\times$ luminance intensification would be very much larger [4]). In fact, such an improvement would be

[1]) M. C. Teves and E. Tol, Electronic intensification of fluoroscopic images, Philips tech. Rev. **14**, 33-43, 1952/53.
[2]) A. Rose, The sensitivity performance of the human eye on an absolute scale, J. Opt. Soc. Amer. **38**, 196/208, 1948.
[3]) R. E. Sturm and R. H. Morgan, Screen intensification systems and their limitations, Amer. J. Röntg. Rad. Ther. **62**, 617-634, 1949.
[4]) H. R. Blackwell, J. Opt. Soc. Amer. **36**, 624, 1946.



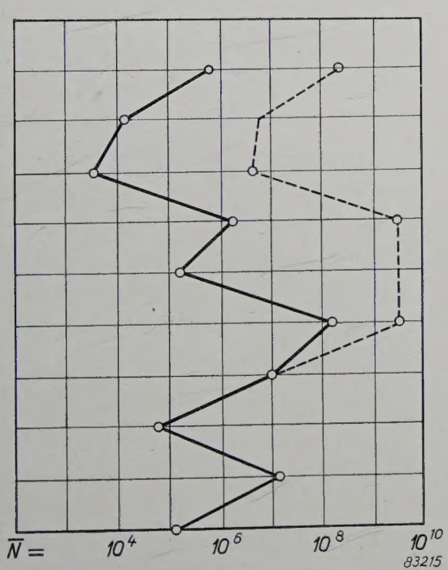
Stage of image transmission	Particles	$\overline{N}$ without I.I.	$\overline{N}$ with I.I.
On object	X-ray quanta	2.5×10^5	2.5×10^5
Transmitted by object	,,	5×10^3	5×10^3
Absorbed by fluorescent screen .	,,	4×10^3	1.2×10^3
Emitted by fluorescent screen .	Light quanta	4.5×10^6	6×10^5
Emitted by photo-cathode . .	Electrons		6×10^4
Emitted by viewing screen . .	Light quanta		6×10^7
In eye pupil	,,	1.2×10^3	4×10^5
Absorbed by retina	,,	3×10^1	4×10^3

Fig. 1. Average number of quanta or particles ($\overline{N}$), for a round detail 2 mm in diameter, effective for 0.2 sec, in different image-stages in fluoroscopy without the image intensifier (dotted line) and with it (full line).
Object: 8 cm "Philite" + stationary scatter grid. Distance to focus 90 cm. 40 kV, 1 mA.

obtained if the light from the screen were generated, not by X-rays, but by a very much larger number of relatively low-energy quanta.

The number of quanta for miniature radiography with and without the image intensifier are shown diagrammatically in *fig. 2*. Here, the time factor is not determined by the fixed period already referred to (0.2 sec), but depends upon the exposure time, since the photographic emulsion stores all the radiation imparted to it. However, the integration time of the eye is involved in the actual examination of the radiograph (last two points in fig. 2).

The radiograph (without image intensifier) refer-



Stage of image transmission	Particles	$\overline{N}$ without I.I.	$\overline{N}$ with I.I.
On object	X-ray quanta	2.2×10^8	7.5×10^5
Transmitted by object	,,	4.5×10^6	1.5×10^4
Absorbed by fluorescent screen	,,	3.5×10^6	3.5×10^3
Emitted by fluorescent screen	Light quanta	4.0×10^9	1.8×10^6
Emitted by photo-cathode . .	Electrons		1.8×10^5
Emitted by viewing screen. . .	Light quanta		1.8×10^8
On photographic emulsion . . .	,,	1.6×10^7	10^7
In photographic emulsion . . .	Blackened grains	5×10^4	6×10^4
In eye pupil . . . } per 0.2 sec	Light quanta	1.5×10^7	1.5×10^7
Absorbed by retina } per 0.2 sec	,,	2.5×10^5	2.5×10^5

Fig. 2. Average numbers of quanta or particles ($\overline{N}$), per detail 2 mm in diameter, effective in miniature radiography without the image intensifier (dotted line) and with it (full line).
Without the image intensifier: Fluorescent screen photographed with a mirror camera, $f/d = 1$, on 70 mm film ("Scopix Ortho"). Total reduction 7 ×. Exposure 40 kV, 180 mA sec.
With the image intensifier: Viewing screen of the image intensifier photographed through an optical system (two lenses: $f/d = 1.5$, f = 55 mm, and $f/d = 2.0$, $f = 75$ mm) on 35-mm film (Agfa "Fluorapid"). Total reduction 6.5 × (that is, reduction in image intensifier 9 ×, optical magnification 1.4 ×). Exposure 40 kV, 0.6 mA sec.
Object: 8 cm "Philite" + stationary scatter grid. Distance to focus 90 cm.

red to in fig. 2 was taken with the aid of a fast mirror camera. Owing to the low aperture ratio at the object side of this system, only a small fraction (roughly 0.4%) of the light from the fluorescent screen is photographically effective. Roughly 70 X-ray quanta must be absorbed by the fluorescent screen to produce enough light to cause the subsequent development of one silver grain in the film emulsion; hence the number of silver grains determines the theoretical limit of contrast. The precise relationship between the density fluctuations and the relative standard fluctuation in the number of grains per object-detail is not known. It is probably associated with the contrast (γ) of the emulsion. However, it is reasonable to suppose that unless the density is very large, its fluctuations will decrease as the number of grains per individual detail increases (that is, as the size of the grains decreases).

In radiography with the image-intensifier, as referred to in fig. 2, a roughly 1.4 times enlarged photograph of the viewing screen is taken on the film with the aid of an optical system. As in fluoroscopy, the increase in luminance compensates for the loss of light in the optical system. Hence each X-ray quantum gives rise to several silver grains (roughly 20) in the developed photographic emulsion. As in fluoroscopy with the image intensifier, then, the number of X-ray quanta absorbed by the initial fluorescent screen of the intensifier determines the theoretical limit of contrast.

With full size radiography, almost all the light from the two screens (so-called "intensifying screens") is effective, because the film is in actual contact with the screens. Measurements of the numbers of light quanta involved have shown that the smallest number (that is, the fluctuations) is governed in this case by the number of X-ray quanta absorbed by the screens.

Given the value of k, then, $C_{\min} = k/\sqrt{N_{\min}}$ can be calculated from the measured numbers of quanta, for object detail of any size.

Experimental results

The next step is to determine by experiment to what extent the theoretically established threshold of perception is approached in fact.

Such measurements can be carried out with the aid of an X-ray phantom, as described in an earlier issue of this Review [5]).

The present measurements were carried out with a modified phantom provided by Prof. G. C. E. Burger. In principle, it comprises a number of plates of "Philite" (a phenol resin) one of which, known as the "phantom plate", contains several cylindrical holes of different diameters and depths. The dif-

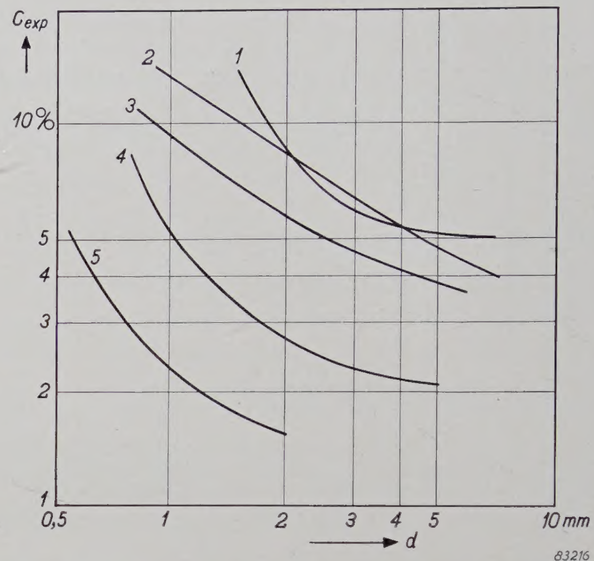


Fig. 3. Example of contrast-detail diagrams obtained by experiment.
Object: 8 cm "Philite" + scatter grid.
Distance to focus: 90 cm.

1:	Fluoroscopy without image intensifier:	75 kV; 4 mA
2:	Fluoroscopy with image intensifier:	67 kV; 0.1 mA
3:	Fluoroscopy with image intensifier:	67 kV; 0.2 mA
4:	Fluoroscopy with image intensifier:	67 kV; 3 mA
5:	Full-size radiograph on "Curix":	67 kV; 3 mA sec

ferences in depth of the holes correspond to differences in absorption, and therefore to differences in intensity of the X-radiation passing through the

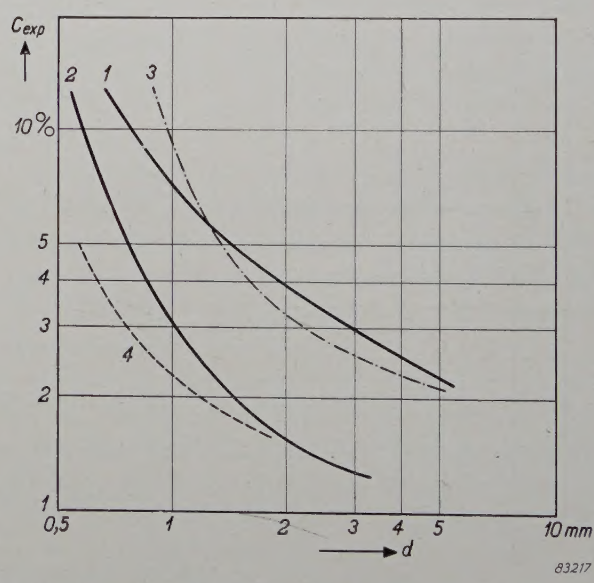


Fig. 4. Example of contrast-detail diagrams obtained by experiment, analogous to fig. 3.
Object: 8 cm "Philite" + scatter grid.
Distance to focus: 90 cm

1:	Radiograph with I.I., "Fluorapid";	67 kV; 0.2 mA sec
2:	Radiograph with I.I., "Micro-File";	70 kV; 5 mA sec
3:	Miniature radiograph (mirror camera without I.I.), "Scopix";	67 kV; 14 mA sec
4:	Full-size radiograph on "Curix";	67 kV; 3 mA sec

[5]) G. C. E. Burger, Phantom tests with X-rays, Philips tech. Rev. 11, 291-298, 1949/50.

plate (frequently but misleadingly called "X-ray contrast"). A number of observers then indicate, either during fluoroscopy or on a radiograph of the phantom, which of the holes they are just able to see. Curves plotted from the depth and diameter of these just perceptible holes, as shown in *figures 3* and *4*, thus represent the boundary between perceptible and imperceptible contrast (C_{exp}) plotted against the diameter of the object detail.

Comparison of experimental and theoretical results

It is evident from figures 3 and 4 that in fact the measured curves are not straight, as predicted from the theory. However, the fluctuation theory holds good only for an ideal apparatus; it takes no account of imperfections, such as the invariable blurring of the image on fluorescent screens, the loss of contrast in the image intensifier, and the limited contrast sensitivity of the eye.

In most fluorescent screens, for example, the blurring exceeds 0.4 mm, and therefore precludes the resolution of detail below a certain size, depending upon the contrast.

What is the situation with regard to detail which is not unduly small, that is, say, 2 mm in diameter? Measurements to determine, for various fluoroscopic and radiographic methods, by what factor the experimental lower limit of perceptible contrast (C_{exp}) exceeds the fluctuation contrast (C_{fluct}) show that this factor is not constant (see last column of *Table I*). The extreme values occur in image intensifier fluoroscopy with X-rays of low intensity (2.2) and image intensifier radiography on film of low sensitivity (11.5); an intermediate value (4.5) is found for image intensifier radiography on sensitive film. The smaller the number of X-ray quanta employed (say, in image intensifier radiography on sensitive film), the higher C_{fluct} and the smaller the ratio C_{exp}/C_{fluct}. A ratio $C_{exp}/C_{fluct} = 4.5$ must be very close to the optimum. The lowest ratio, viz. 2.2, occurs in image intensifier fluoroscopy with X-rays of low intensity. However, it does not necessarily follow that $k = 2.2$ or, more precisely, that an X-ray contrast equal to 2.2 times the average relative standard fluctuation is invariably perceptible. The probability of a moment with a low fluctuation level increases with the period of observation, so that relatively longer examination may enable the observer to perceive a contrast lower than that corresponding to $C_{min} = k/\sqrt{\bar{N}_{min}}$ [6]).

In view of these arguments, we consider that $k = 3$ is a good approximation to the optimum value.

Table I. Minimum contrast observed (C_{exp}), minimum number of quanta ($\bar{N}_{min}$), the fluctuation contrast computed from it (C_{fluct}), and the ratio C_{exp}/C_{fluct}, for the observation of a detail 2 mm in diameter in a "Philite" phantom 8 cm thick, by different methods.

Method	kV	mA or mA sec	C_{exp} %	$\bar{N}_{min}$	C_{fluct} %	$\frac{C_{exp}}{C_{fluct}}$
Fluoroscopy without Image Intensifier	75	4	8	1.2×10^3	2.9	2.8
Fluoroscopy with Image Intensifier	67	0.2	4.4	2.5×10^3	2.0	2.2
Radiography with Image Intensifier on "Fluorapid" 35-mm film. Optical system $d/f = 1:4.5$	67	0.2	4	12.5×10^3	0.89	4.5
Miniature radiography without Image Intensifier; mirror camera	67	14	3.25	30×10^3	0.58	5.6
Fluoroscopy with Image Intensifier	67	3	2.8	37.5×10^3	0.52	5.4
Radiography with Image Intensifier on "Micro-File" 35-mm film. Optical system $d/f = 1:2$	67	1.5	1.55	100×10^3	0.31	5.0
Radiography with Image Intensifier on Pan F 35-mm film. Optical system $d/f = 1:4.5$	67	2	2.6	125×10^3	0.28	9.3
Full-size radiography	67	3	1.5	450×10^3	0.15	10.0
Radiography with Image Intensifier on "Micro-File" 35-mm film. Optical system $d/f = 1:4.5$	67	8	1.6	540×10^3	0.14	11.5

For the full-size radiograph and for the image intensifier radiograph on fine-grain film, the experimental values of C_{exp}/C_{fluct} are relatively high (>10). Here, then, the perception of a round detail 2 mm in diameter is virtually independent of the quanta fluctuations, but is governed almost exclusively by imperfections in the apparatus. Although difficult to eliminate such imperfections are not of a fundamental nature.

Direct perception of the quanta fluctuations

Confirmation of the above arguments is obtained by the fact that the X-ray quanta fluctuations can be observed direct in the X-ray image. In image intensifier fluoroscopy with X-rays of not unduly high intensity, the image exhibits a certain

[6]) Incidental, favourable fluctuations are of no real value in radiography, because they never cover the entire field.

amount of "noise". This noise is closely connected with the relatively small number of X-ray quanta involved in the forming of the luminous image. The higher the intensification factor of the image intensifier, the more readily are the fluctuations perceived by the observer, especially when the viewing screen is observed through an optical system of high magnification.

As already explained, in photographs taken with an image intensifier we generally find an appreciable difference between the experimental threshold of perception and the theoretical threshold determined by the quanta fluctuations (high ratio C_{exp}/C_{fluct}). Hence it is unlikely that the fluctuations will be perceptible in such radiographs. However, they are seen distinctly in image intensifier radiographs taken with a relatively very much smaller amount of X-radiation but a faster optical system. *Fig. 5* gives

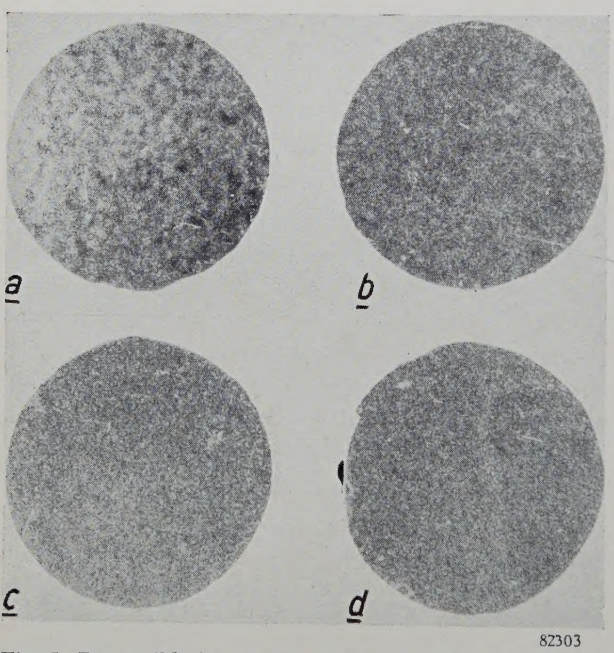


Fig. 5. Perceptible X-ray fluctuations in radiographs taken with the aid of the image intensifier. The photographs were taken with different stops, becoming smaller from *a* to *d*.

an example. Here we have four reproductions of parts of image intensifier photographs. They differ only in respect of the amount of X-radiation per photograph, which is in the ratio $a:b:c:d=1:5:32:160$; this variation was made possible by varying the stop of the lens system.

It can be seen that the photographs differ quite appreciably. Photograph *a*, for example, taken with the maximum lens aperture of the system, shows a coarser structure than the others. The high intensification produced by the intensifier, combined with the use of the maximum stop, enabled this photograph to be taken with a relatively small number of X-ray quanta; the very noticeable local fluctuations in density arise from the fact that each X-ray quantum blackens an individual cluster of grains in the emulsion. Photograph *d*, taken with a very much smaller aperture, necessitated a very much larger number of X-ray quanta to expose the grains. Because the number of X-ray quanta and hence that of grain clusters in *a* is very much smaller, the relative statistical fluctuation in the number of individual aggregates is more noticeable. Hence the grain distribution of photograph *a* is appreciably less uniform than that of photographs *c* and *d*. A fine rose on a watering can sprinkles more evenly than a bucket.

Fundamental and practical advantages of the image intensifier

The advantages of the image intensifier as applied to fluoroscopy and radiography will be evident from fig. 1 and fig. 2. Without the intensifier, only a small proportion of the X-ray quanta are absorbed by the screen, on an average, in fact, only 1 in every 100, is effective; hence the relative value of the fluctuations is roughly 10 times the fluctuation inherent in the quanta absorbed. Accordingly, the detail perception is then fundamentally inferior to that obtained with the image intensifier, which makes all the X-ray quanta absorbed effective. Here, every quantum of radiation absorbed by the screen gives rise to a threefold stimulus in the retina, or exposes several silver grains in the film (e.g. 20—30), the precise number depending upon the type of film and the aperture ratio of the optical system.

Certain conclusions regarding the observation of not unduly small detail (one or two mm) with low contrast may be drawn from the values of C_{exp}/C_{fluct} established.

In fluoroscopy with the image intensifier, a very close approximation to the theoretical threshold of perception is reached experimentally; hence we cannot expect to gain very much from technical improvements when employing the conventional examination procedure.

Again, in image intensifier radiographs taken on 35-mm film with the aid of a fast optical system, the threshold of perceptibility is governed, in practice, by the fluctuations of the X-ray quanta. Consequently all that can be done to obtain more information in such a case is to increase the X-ray dose: a film of finer-grain may then be used. Ultimately, then, a limit is imposed by the imperfections of the apparatus.

Finally, let us consider one or two values taken

from figures 3 and 4 to demonstrate the advantages of the image intensifier technique. It is seen that the X-ray dose to observe a given threshold-contrast with the image intensifier is only 1/40 of that required in conventional fluoroscopy without the intensifier. The dose to take an image intensifier photograph on 35-mm film is a factor of 70 smaller than that required for a 70-mm miniature radiograph taken without the image intensifier, the film-sensitivity being the same in both cases and the X-ray images being reproduced roughly 7 times smaller on the film. There is very little difference in detail perception as between the two photographs. This is very important from the point of view of the filming of moving organs with the aid of the image intensifier.

With a very fine-grain film, the image intensifier enables us to take 35-mm photographs of a quality comparable with that of a full-size radiograph; moreover, if a fast optical system is employed, the dose required is several times smaller than in conventional radiography.

III. OPTICAL AIDS FOR THE IMAGE INTENSIFIER

by P. M. van ALPHEN. 621.386.8:616-073.75:621.383.8:535.82

It is neither necessary nor customary to employ optical aids in the examination of an X-ray image on a conventional fluorescent screen. However, to resolve the detail of the image, the eye must be properly adapted to the low luminance level of the screen.

With the image intensifier, however, precisely the reverse holds good. Although bright enough to be examined under ordinary room lighting, the visible image formed in the intensifier is so reduced by the electron optical system that optical instruments are required to enable the details to be perceived.

The image intensifier therefore necessitates a different approach, not only to fluoroscopy, but also to photographic work. The mirror camera, although eminently suitable for photographing the conventional low-luminance X-ray image, by virtue of its high aperture ratio, cannot be used without modification to photograph the relatively small image in the intensifier.

The problem of magnifying small objects for observation or photography is of course not new and many ways of doing it are known. The magnifying glass, microscope, telescope, camera, etc. are well-known examples. It is however, desirable to review the general requirements to be imposed on an optical system for use with the image intensifier. In so doing, we shall also discuss various designs examined during the development of the Philips image intensifier.

Quantities and concepts used in photometry

As an introduction to the above-mentioned discussion, let us consider the quantities employed as measures of light, quantities which are frequently misinterpreted.

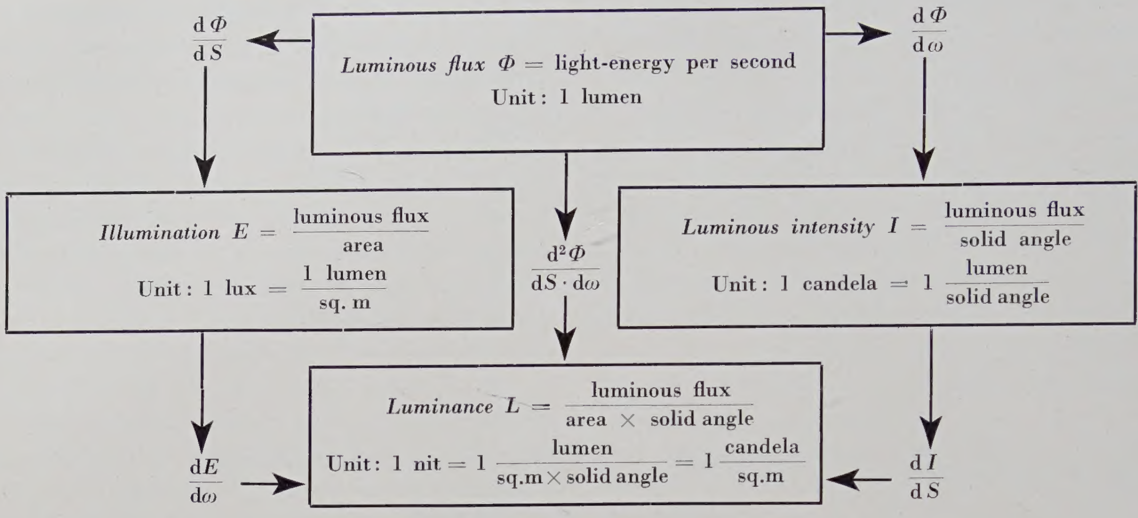
A light source radiates energy; that part of this radiant energy whose wavelength is within the visible spectrum forms the luminous flux (unit: the lumen).

Luminous flux, then, is the light proceeding from the entire surface of the light source in all directions. For certain problems it is necessary to determine the distribution of this flux in space; in other cases, we are more concerned with the flux-distribution as between different points on the surface of a light source or an illuminated surface.

In many cases we require the quantity luminous flux (throughout the solid angle) per unit area; in other cases we wish to know the luminous flux (from the whole of a surface) in a given direction that is, per unit solid angle. We may also go a step further and consider the luminous flux emitted by a given surface in a certain direction. Thus the overall luminous flux output may be divided according to area or direction, or area *and* direction. The quantities thus defined have acquired individual names, i.e. illumination level (or briefly illumination), luminous intensity and luminance (or brightness), respectively. They are shown diagrammatically in *fig. 1* and *Table I.*

How, then, are these quantities affected by such optical elements as lenses and mirrors? Since optical systems do not generate light, they do not increase the overall luminous flux, which therefore remains constant, apart from some absorbtion in the system. However, the illumination and luminous intensity do not necessarily remain constant. The luminous flux can be concentrated, with the aid of a lens or mirror, upon certain points (or areas), or in certain directions (solid angles). This concentration may produce substantial changes in both luminous

Table I. Diagram of the relationship between light quantities.



intensity and illumination [1]). The luminance however, is not affected; since the luminous flux per unit area and per unit of solid angular measure is associated with the flux density of the radiation, or radiance, it is a property of the light source. Hence it cannot be increased by means of an optical system.

If the luminance could be so increased, we would observe the very strange phenomenon of energy (in this case light) being transformed from a state of low concentration to a state of higher concentration without the performance of work. It is evident, then, from the reversibility of light radiation that luminance is affected only by absorption.

Let us now consider the relationship between luminous flux (Φ) and luminance (L) (*fig. 2*). It is seen that, at a given luminance level, the luminous flux increases with the solid angle and with the area of surface S. This holds good for a luminous, as well as for an illuminated surface. However, it should be borne in mind that L may also depend upon direction. In the simplest case of a radiator, whose luminance is constant in all directions, that is, a radiator obeying Lambert's law, the luminous flux is:

$$\Phi = \pi L S \sin^2 \tfrac{1}{2}\varphi \quad \ldots \ldots \quad (1)$$

where φ is the apex angle of the cone of flux.

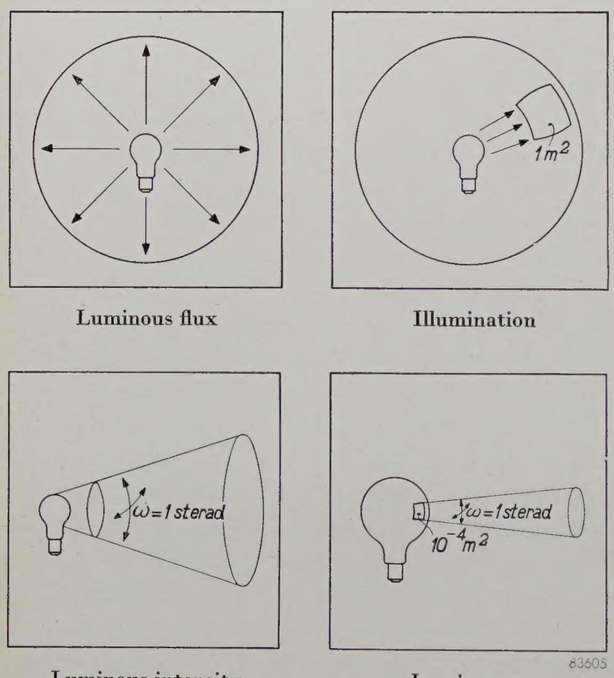


Fig. 1. The four photometric light quantities. Luminous flux is the overall light-output of the lamp. Illumination is the luminous flux incident upon 1 sq. m. Luminous intensity is the luminous flux radiated by the lamp per unit solid angle. If the light is simply freely radiating, light initially within a certain solid angle remains within it; hence luminous intensity is independent of the distance to the light source. Luminance (brightness) is the luminous intensity per unit surface area (sq. m or sq. cm) of the light source; hence it is also the luminous flux per unit area and per unit solid angle.

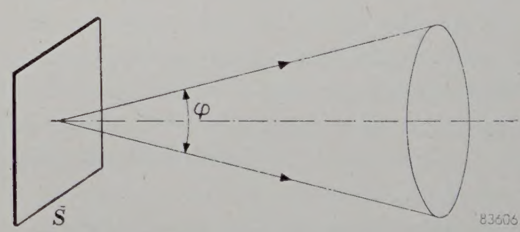


Fig. 2. The luminous flux Φ radiated within an angle φ by a surface with area S and luminance L in accordance with Lambert's law, is $\pi L S \sin^2 \frac{1}{2}\varphi$.

[1]) The simplest example of this is a candle with a plane mirror behind it. The mirror increases the the luminous intensity to two candles, but reduces the solid angle containing this luminous intensity to 2π, that is, the half of a sphere.

Application to optical systems

We shall now consider the above formula in four different cases:

1) the human eye;
2) a camera;
3) an arbitrary optical system;
4) the image intensifier.

The sensation produced in the human eye is governed by the strength of the stimulus imparted to the optic nerve in the retina. This stimulus depends upon the amount of luminous flux Φ entering the eye, for which formula (1) holds good. For the purpose of our argument, the area S of a retinal element may be considered constant (fig. 2). Let Φ be the vertical angle of a cone whose apex is on the retina and whose base is the pupil of the eye. For a high enough luminance level, this angle is constant. The light sensation, or subjective brightness is therefore governed entirely by the luminance L. However, it is here assumed by implication that the cone φ is completely filled by light rays, or, in other words, that the eye pupil is fully illuminated by the optical system through which it is looking. To satisfy this condition, the smallest aperture through which the light cone emerges from the optical system, that is, the so-called exit aperture must be larger than the pupil of the eye. Since the eye pupil distends according as the luminance decreases (*fig. 3*) it is necessary, therefore, in designing an optical system, to pay due regard to the luminance range for which it is to be employed (day or night glasses).

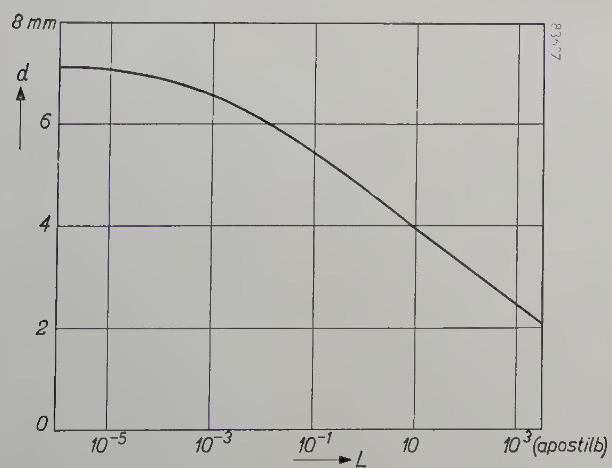


Fig. 3. Diameter (d) of the pupil of the human eye, plotted against the luminance L.

The luminous flux is also important in cameras; however, this statement requires elucidation. In referring to the luminous flux received by the optical system of the camera from the object, and projected onto the photographic film, we must state the area upon which the flux impinges, since the required exposure is shorter, the higher the illumination level $\Phi/S = \pi L \sin^2 \frac{1}{2}\varphi$. Given L, that is, the luminance of the object, we are still free to choose $\sin \frac{1}{2}\varphi$ as large as we please. When this has been done, we also establish Φ/S, and therefore the exposure; the latter does not vary with the focal length, but the size of the image is, of course, proportional to the focal length. On the other hand, if the luminous flux is fixed (e.g. because it is supplied by another optical system) minimum exposure may be obtained by reducing the size of the image on the film as far as possible. This is done by using a lens of suitable diameter and minimum focal length.

In practice, the problem is usually more complex than the above argument suggests, since not only the exposure, but also the sharpness of the picture, the grain of the emulsion, the price of the optical system and the variation of $\sin \frac{1}{2}\varphi$ with the magnification, are involved.

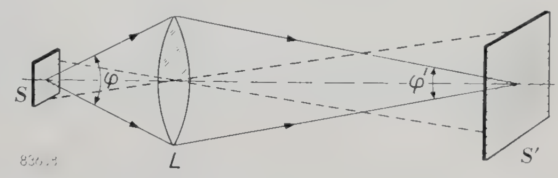


Fig. 4. Derivation of the sine condition. Lens L transforms area S into S' and angle φ into φ'.

By applying equation (1) to a lens or optical system, we obtain a simple derivation of a formula referred to variously as the Helmholtz, Huygens, or Lagrange formula, but more often called Abbe's sine law. Leaving absorption and reflection losses out of account, the luminous flux Φ' inherent in the image is equal to the effective flux intercepted by the lens (Φ; see *fig. 4*). Hence we have:

$$\Phi = \Phi', \quad \text{or} \quad \pi L S \sin^2 \tfrac{1}{2}\varphi = \pi\, L'S' \sin^2 \tfrac{1}{2}\varphi'.$$

We have already seen that the luminance remains constant; hence $L' = L$, and

$$\frac{S'}{S} = \frac{y'^2}{y^2} = \frac{\sin^2 \frac{1}{2}\varphi}{\sin^2 \frac{1}{2}\varphi'},$$

or

$$N = \frac{y'}{y} = \frac{\sin \frac{1}{2}\varphi}{\sin \frac{1}{2}\varphi'} \quad \ldots\ldots \quad (2)$$

where N is the magnification, and y' and y are the diameters of the image and the object, respectively. From the point of view of illumination, then, an optical lens is a transformer of area and angular aperture, the transformation invariably taking place in such a way that luminous flux and luminance remain unchanged, whereas luminous intensity and illumination may vary.

To come back to the image intensifier, it produces two different intensifications. Firstly, the high voltage on the tube imparts extra energy to the photo-electrons, thus making the fluorescence of the viewing screen brighter than that originally produced on the photo-cathode; this is known as the lumen intensification of the tube. Secondly, by virtue of the N-times electron-optical reduction, the light thus intensified proceeds from an area smaller than that of the photo-cathode, so that here (as opposed to purely optical reduction) an extra luminance-gain of N^2 is obtained. This factor contributes the most to the overall luminance intensification. The optical system through which the tube is then viewed must clearly be so designed as to enable the N-times smaller image to be seen without any loss of luminance.

Formula (2) enables us to determine the maximum magnification obtainable, without loss of luminance, by means of an optical system. As we have already seen, the whole area of the eye pupil (say, 8 mm in diameter) must be filled with light. The apex of the light cone is on the image observed, i.e. at the closest distance of distinct vision, say, 25 cm. Hence $\sin \frac{1}{2}\varphi = 4/250 = 0.016$. It will be evident that the maximum vertical angle of the cone intercepted by the optical system is 180°, which is consistent with $\sin \frac{1}{2}\varphi = 1$; hence the maximum magnification enabling the light to fill the whole eye pupil is $1 : 0.016 = 60\times$. Any further magnification reduces the luminance of the observed image. In reality, however, the vertical angle of the intercepted light cone is invariably very much smaller than 180°; the maximum permissible magnification is therefore also smaller.

We shall now describe a number of different optical systems, outlining the conditions governing their use. It is necessary to point out, however, that one very important factor, that is, the convenience of the observer, is virtually ignored in these discussions. In practice, it is usually preferable to accept a slightly less perfect but easily adjustable system to one which is perfect only in theory.

Optical aids to fluoroscopy

The magnifying glass

The simplest means of observing the small image on the viewing screen of the image intensifier tube is an ordinary magnifying glass. This has not been used so far, however, for the reasons given below. To enable the image to be seen with both eyes, the magnifying glass must be employed as a reading glass. The magnification is then relatively weak; hence it would impose a limit on the permissible electron-optical reduction in the image intensifier. We have already seen that the luminance intensification, which is most important in fluorsocopic examinations, increases as the square of this reduction. A loss of a factor of 4 in electron-optical reduction is equivalent to a loss of a factor of 16 in luminance.

Within the required field of view (14 mm), a very much stronger magnification can be obtained by placing the glass to only one eye. However, both the eye and the glass must then be brought close to the viewing screen, a condition which cannot always be satisfied.
Moreover, the principal objection to the use of a magnifying glass is that the electron-optical system of the image intensifier produces an inverted image on the viewing screen; when the latter is observed through a magnifying glass, then, the image of the object is seen upside down. This is very distracting to a doctor unaccustomed to such image inversion in ordinary fluoroscopy. It can, of course, be corrected by means of image-erecting mirrors or a system of prisms, but they detract from the essential simplicity of the equipment; moreover, they preclude the use of a strong magnifying glass, since there is then no room to place them in the path of the rays.

Microscopes

These considerations have led to the idea of employing one lens to erect the image and another, a magnifying glass, for viewing it. This is essentially the same arrangement as in a microscope, where the objective functions as an image-erecting lens and the eyepiece is, in effect, a magnifying glass. Now, to restore the image to its original size we require a magnification of roughly $10\times$, which could be obtained with an eyepiece of, say, $5\times$, and an objective of $2\times$ magnification. The diameter of the exit pupil depends upon the aperture of the microscopic objective, which in a relatively weak objective, as here considered, is not very large. We employed a microscope having a numerical aperture of 0.07 and an exit aperture between 4 and 5 mm in diameter. It is smaller than the pupil of a dark-adapted eye, and would therefore be a possible cause of loss of luminance. However, practical experience has shown that with the $1000\times$ intensification, dark-adaptation of the eye virtually never occurs.

Binocular microscope

Viewing with both eyes is usually less fatiguing than with one eye. However, we wish to avoid the

binocular arrangement employed for ordinary microscopes of this type, that is, a semi-transparent mirror or prism distributing the available light evenly between both eyes, because it reduces the luminance at least by half. We are therefore compelled to double the light-gathering power of the system and employ an objective with a very large exit pupil, or, as in Greenough's microscope, two objectives, and two eyepieces, side by side.

an angled arrangement, a full description of which will be given in the following article (IV).

Another possibility will now be described. In it, the monocular microscope already described is retained for viewing, but two mirrors, parallel to each other and at roughly 45° to the path of rays, are introduced into their path. They produce a lateral displacement of the image, but do not rotate it (see IV). By making the viewing system rotate

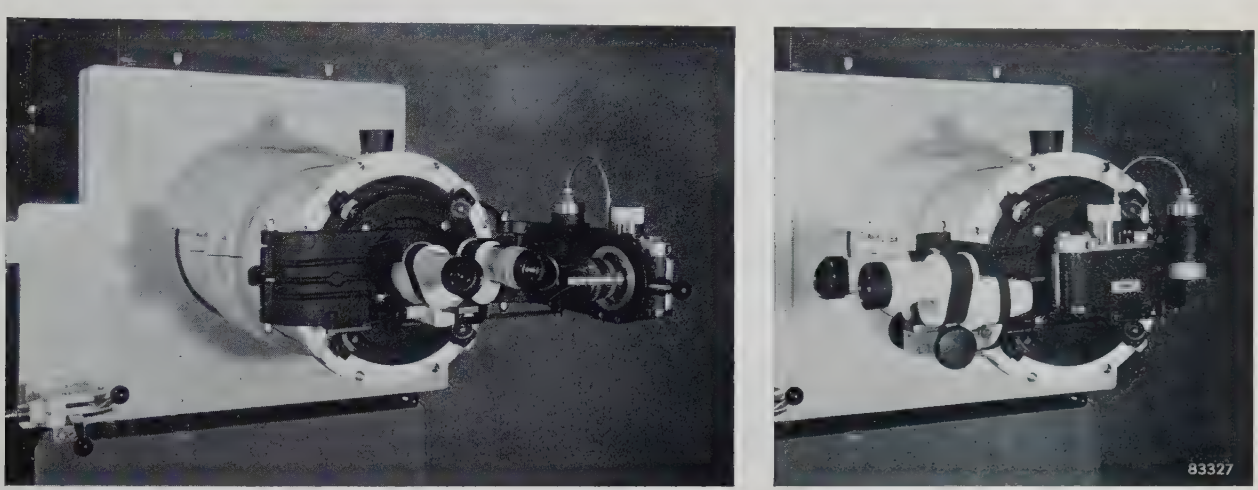


Fig. 5. Binocular microscope and camera, mounted so that they can be swung alternately into position in front of the image intensifier. The left-hand picture shows the microscope in use; in the right-hand picture the camera is in use.

Most of the microscopes of this pattern now on the market contain Porro image-erecting prisms; hence they are not very suitable for our purpose. Accordingly, we began our experiments with two monocular microscopes side by side at an angle of 18°. With this arrangement, however, it is rather difficult to adapt the system to individual eye-spacing (varying from 55 to 75 mm), without affecting the focus. Prisms are therefore used (despite some light-loss) to deflect the path of the rays slightly, thus enabling the distance between the eyepieces to be varied by rotating them about the optical axis, and differences in focussing as between individual observers to be compensated by adjusting the two eyepieces separately. The binocular microscope thus obtained, combined with a camera, is shown in *fig. 5*.

Movable mounting

The above mentioned arrangement is very useful for an image intensifier operated in a fixed position. With an image intensifier so mounted that it can be turned in all directions, however, we must pay more attention to the problem of bringing the eyepiece within easy reach of the eye. From this point of view, a monocular system, rotated by means of movable mirrors or prisms, is best. It is, in effect,

about the axis of the image intensifier tube, the eyepiece can be adjusted to the eye-level of the particular observer (*fig. 6*). Moreover, by allowing the second mirror to tilt slightly about an axis perpendicular to the plane of the drawing, the

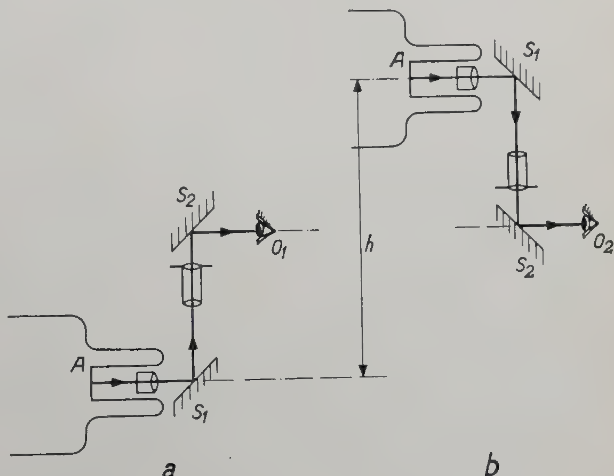


Fig. 6. Periscope optical system. (*a*) Two mirrors parallel to each other (S_1 and S_2) bend the path of rays, but do not change the position of the observed image. (*b*) By rotating the whole system about axis AS_1, the image intensifier can be raised or lowered a distance h without varying the level of the eye (O_1 or O_2). The direction of observation can be varied by tilting mirror S_2 about an axis perpendicular to the plane of the drawing.

viewing direction can be adjusted to a comfortable head position. With some movable systems, the thought of peering into the eyepiece tends to produce a slight feeling of apprehension: the observer is aware that it may hit him in the eye when moved. However, this can be avoided, either by providing a suitable head support (see IV), or by so designing the optical system that the point where the eye must be to observe the entire image, that is, the exit pupil of the instrument, is some distance away from the metal parts of the instrument. Moreover, if the exit pupil be as large as possible, the eye will not be restricted quite so much to one particular viewpoint.

With such an arrangement, it is not easy to find the proper position for the eye in relation to the system, if it happens that the eye is not in the path of the rays, the observer cannot see the image and does not know which way to move the head in order to see it. This problem has now been solved in the following manner (*fig.* 7). A piece of frosted glass is introduced into the path of rays at the point (B) where an image is formed by the objective (L_1). The glass is so frosted as to diffuse only slightly in lateral directions, and transmits mostly in the direction perpendicular to its surface, that is, along the axis of the system. This frosted glass screen is viewed through the eyepiece (L_2), then employed, in effect, as a magnifying glass, Looking obliquely through L_2 towards the frosted screen, the observer sees an image, but a faint one owing to the very limited diffusion of the glass in the non-axial direction towards his eye. However, he has only to move his head to perceive in which direction he should move it to increase the apparent luminous intensity of the image; in this way, the position of maximum image intensity is soon located. It lies precisely on the optical axis of the instrument, that is, on the same line as the above-mentioned exit pupil. When the frosted glass is withdrawn, then, the eye is exactly in the path of rays, and it requires no more than a slight forward or backward movement of the head to observe the entire image plane and its maximum luminance through L_2, which then functions as an eyepiece. If the correct eye-position is lost during the moving of the image intensifier, it is quickly found again by re-inserting the frosted glass in the path of rays. In some cases, where the X-ray dose makes it desirable, the frosted glass may be left in the system; this greatly facilitates the observation, but slightly reduces the luminance and sharpness of the image.

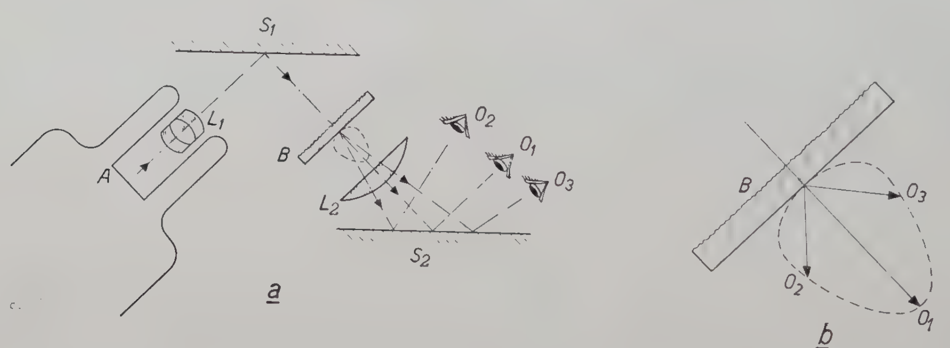


Fig. 7. Principle of the frosted glass view-finder (a). The fast lens L_1 projects an image of A upon mirror S_1, which reflects it into the only slightly frosted glass screen (B). The image on this screen is viewed through a system comprising a magnifying glass (L_2) and a mirror (S_2). The eye is attracted to position O_1 because from here the image is brightest. When the eye is kept in this position and the frosted screen is withdrawn from the path of rays, the image is seen in full brightness. L_1 and L_2 then operate as the objective and eyepiece of a microscope. The diagram (b) shows the diffusing pattern of the frosted glass.

Photographic optical system

There is a wide choice of cameras for recording the image on the viewing screen of the image intensifier. One or two general remarks on the subject may therefore be useful. We have first to consider whether we require single photographs taken at intervals, a series of photographs taken in rapid succession, or cine films to enable us to study movements or sudden effects. When this question is settled, we must decide upon a suitable picture size and choose the lenses with which to obtain it. In this connection, we must also decide on the type of film, and even consider the most suitable design for the image intensifier itself.

Let us now consider the question of film size. Given an image intensifier tube with a viewing screen of a certain luminance, we require an optical system with the highest possible light-gathering power to photograph it. Using the best optical system available, it is possible to intercept only a certain proportion of the luminous flux emitted by the viewing screen; hence it is not advisable to distribute this intercepted flux over a large area of film. Accordingly, we take the film as small as possible, that is, the smallest size consistent with the detail required and the resolving power of the particular photographic material. Another reason for choosing a small film size is that most of the fast optical systems now on the market are designed for miniature film.

Next, we must deal with the problem of forming

an image of an object (the viewing screen) on film of roughly the same size. However, photographic optical systems, and notably the ones considered for our purpose, are designed to form reduced images of large objects, that is, to produce images at the focus. They are less suitable for the formation of full-size images, because in so doing they fail to correct the aberrations in the image [2]). Moreover, with images formed on the scale of 1 : 1, the object and image distances are both equal to twice the focal length of the system; hence the angular aperture ($\frac{1}{2}\varphi$) is only half as wide then, as in the formation of an image at the focus.

At first glance it may seem that we can go a long way towards solving this problem by increasing the size of the viewing screen in the image intensifier tube, that is, by designing the intensifier so as to give a less drastic electron-optical reduction of the image. However, it is readily shown that in fact this would be a mistake, since it would deprive us of part of the luminance-gain from electron-optical reduction, which is one of the principal advantages of our system; although the particular lens would then operate under conditions more favourable as regards angle $\frac{1}{2}\varphi$ (the optimum choice

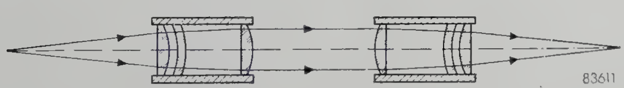


Fig. 8. Two lens systems in tandem: to form an image of roughly full size, two optical systems may be employed, the one with the object, and the other with the image in focus. The rays associated with any given image point are parallel between the two systems.

of optical system and film size is not affected by the supposed smaller electron-optical reduction in the image intensifier), the luminance (L) would decrease as the square of the diameter of the viewing screen. The final result, then, is that the film would receive less light (see equation 1).

However, the problem can be solved in another way, i.e. by the simple expedient of using, two ordinary photographic lens systems in tandem, so that the image produced at infinity by the one is focussed by the other (see *fig. 8*). Thus each lens is utilised in the manner best suited to it, the net angular aperture being twice that of a single optical system forming an image on the scale of 1 : 1.

[2]) This is illustrated most simply by a mirror system: with an infinitely long object distance the parabolic mirror is free from spherical aberration; with a finite object distance, however, it is necessary to employ the focal points of an elliptical mirror.

Although the path of rays between the two optical systems is parallel, they should be placed as close together as practicable; otherwise, rays oblique to the axis may be cut off (vignetting; see *fig. 9*). A certain amount of magnification can be procured

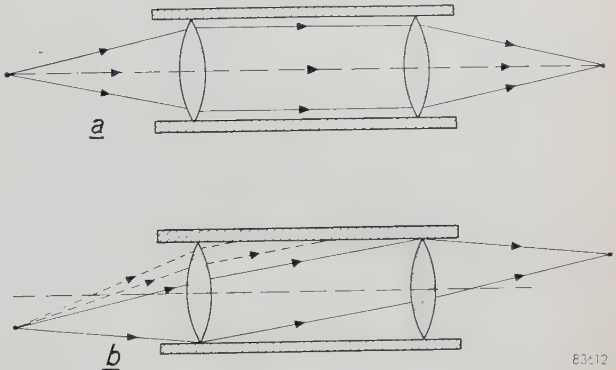


Fig. 9. Vignetting effect. The whole of the beam on the axis, that is, rays corresponding to the centre of the image, is transmitted (a), whereas oblique rays constituting the edges of the image are cut off sharply at one side (b).

with such a system by employing two lenses with different focal lengths, say, $f_1 = 50$ mm and $f_2 = 60$ mm. The magnification is equal to the ratio of the focal lengths: $N = f_1/f_2$.

Using a reflex camera, it is possible to keep the image to be photographed in view until immediately before the exposure. When filming the image, however, we require a view-finder to view the image continuously; also there is not very much space for a viewing system in front of or behind the lens. By placing a small mirror or prism between the two objectives, we gather a certain amount of light from

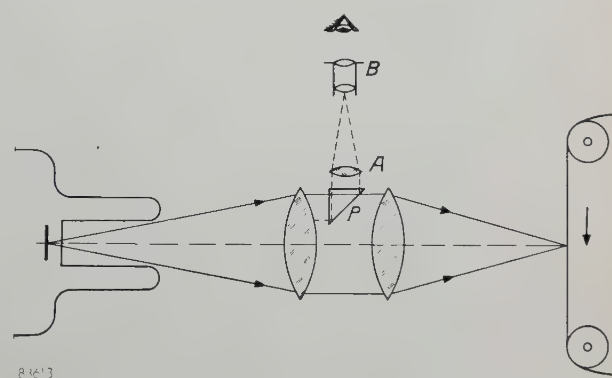


Fig. 10. View-finder for the tandem combination of lenses. Because prism P is placed in the parallel rays, it does not intercept much light. Looking through telescope AB at prism P, the observer sees the object apparently at infinity.

the image at infinity (*fig. 10*), enabling it to be viewed either with the naked eye or through a small telescope during the filming of the image. An alternative method is to provide the shutter of the film camera with a reflecting surface. Such measures have little effect on the photographic optical system.

IV. EQUIPMENT FOR SPOT FILM RADIOGRAPHY INCORPORATING AN IMAGE INTENSIFIER FITTED WITH A PERISCOPE OPTICAL SYSTEM

by H. VERSE *) and H. JENSEN **).

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The radiologist, long accustomed to working with radiographs and a fluorescent screen, is rather at a loss when first confronted with the picture provided by an image intensifier. The picture is brighter, but its location is unconventional. The relatively higher luminance of the image enables him to see that it is green; moreover, his eyes are not dark-adapted and the subjective contrasts appear quite different from those to which he is accustomed. Also, the relatively small field of view (13.5 cm) makes it more difficult for the radiologist to form an overall impression of the particular part of the body examined. Hence he may find that he requires the larger but fainter field of an ordinary fluorescent screen, as well as the image intensifier. A diagnostic apparatus specially designed to meet this need has been built in the X-ray factory of C.H.F. Müller at Hamburg [1]). It is intended to provide the radiologist with facilities for working either with an ordinary fluorescent screen, or with the image intensifier, and facilities for taking either direct full-size radiographs, or miniature fluorographs from the screen of the intensifier. Also it enables him to place the subject upright, prone, or in any intermediate position. The design includes several special features and the image intensifier itself is equipped with a novel viewing optical system to make viewing during the tilting of the subject as convenient as possible.

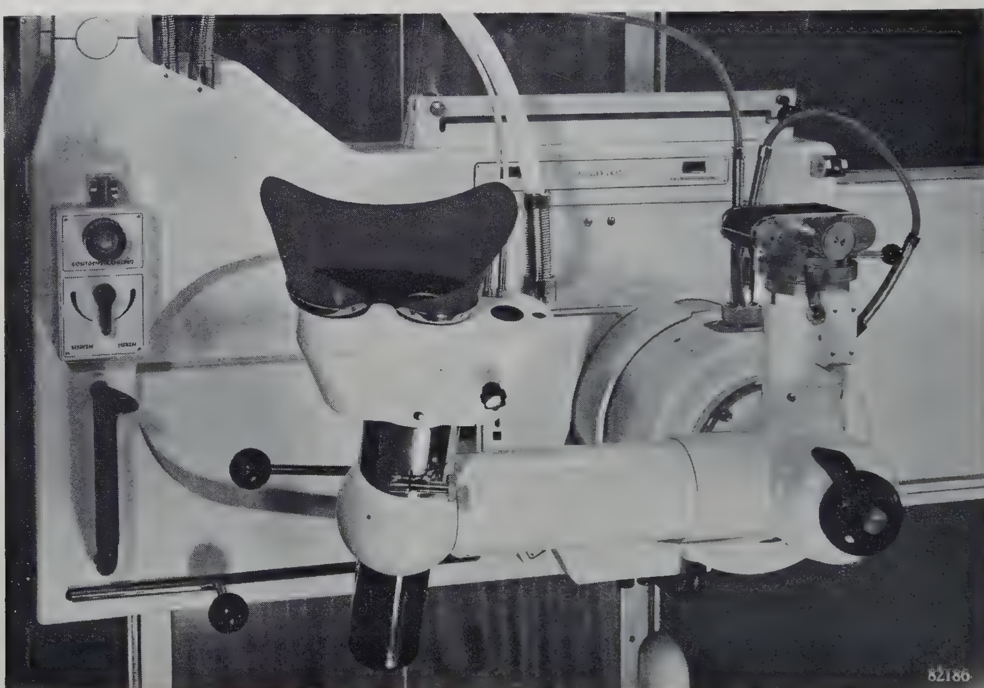

Fig. 1. Periscope viewing system of the "Müller" diagnostic apparatus ZK 100. The cover of the image intensifier tube, to which the system is attached, is seen on the right, and the rubber forehead-support with the eyepiece aperture on the left. The black knob in the bottom right-hand corner is used to deflect the light-rays when required into the camera immediately above it.

Principle of the observation

The viewing optical system (*fig. 1*) is so designed as to enable the observer to stand aside from the axis of the beam, that is, from the patient. The system can be rotated to vary its slant, and thus

*) C. H. F. Müller Aktiengesellschaft, Hamburg.
**) Allgemeine Deutsche Philips Industrie G.m.b.H., Hamburg.

[1]) H. Verse and H. Jensen, Ein Untersuchungsgerät mit Röntgenbildverstärker, Fortschr. Röntgenstrahlen **79**, 115-118, 1953.

enables the direction of view and the height of the eyepiece to be adjusted to the eye-level of the doctor carrying out the examination. From the optical point of view, the system is an angled, rotatable microscope with an optical magnification of 10 times, through which the image of the object is seen restored to its full size. Light rays from the viewing screen of the image intensifier tube (*A*; *fig. 2*) fall upon an objective *O*, and are then deflected by a so-called roof prism *P* along the lateral axis of the periscope (*X*-*X*′). They pass through an erecting prism *Z* (see below) and are then reflected by mirror *S* towards the eye of the observer *E*. The objective *O* forms an enlarged image of the viewing screen *A* at *B*, which is seen further magnified, through lens *L*.

The system is so designed that the section *S*-*L* can be rotated about the axis of the periscope (*X*-*X*′), thus enabling the radiologist to examine the patient in different positions, using only one hand to vary the direction of view and the level of the eyepiece, the other hand remaining free for other adjustments associated with the examination (*fig. 3*). The rotation of section *S*-*L* about axis *X*-*X*′ makes

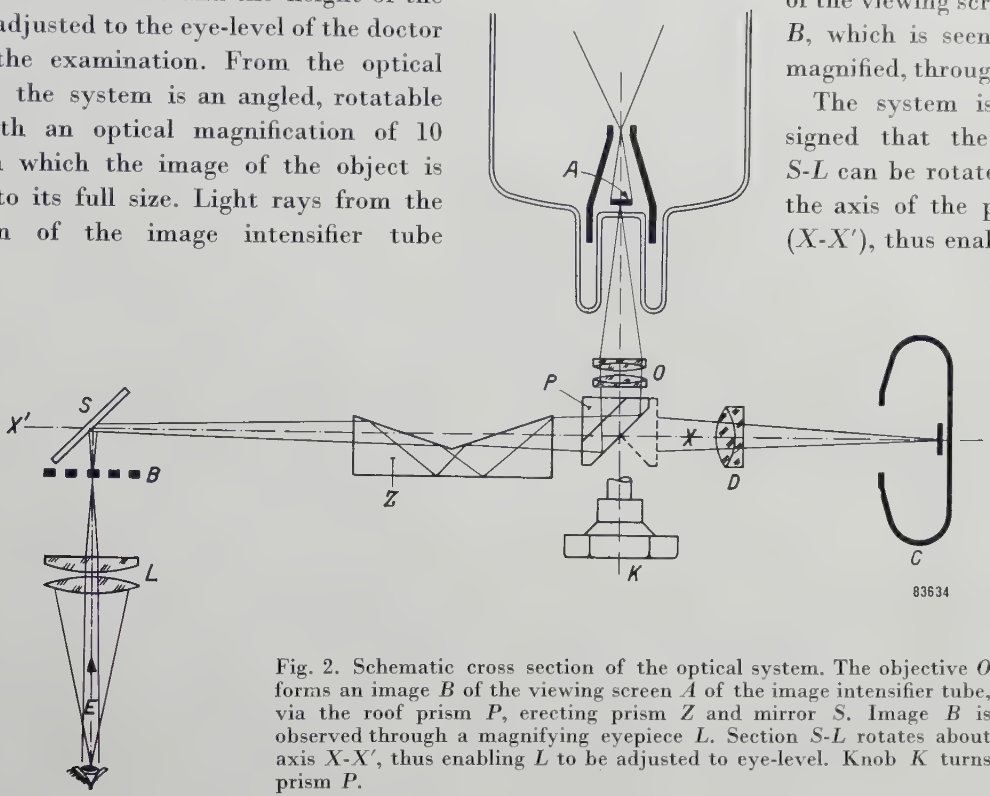

Fig. 2. Schematic cross section of the optical system. The objective *O* forms an image *B* of the viewing screen *A* of the image intensifier tube, via the roof prism *P*, erecting prism *Z* and mirror *S*. Image *B* is observed through a magnifying eyepiece *L*. Section *S*-*L* rotates about axis *X*-*X*′, thus enabling *L* to be adjusted to eye-level. Knob *K* turns prism *P*.

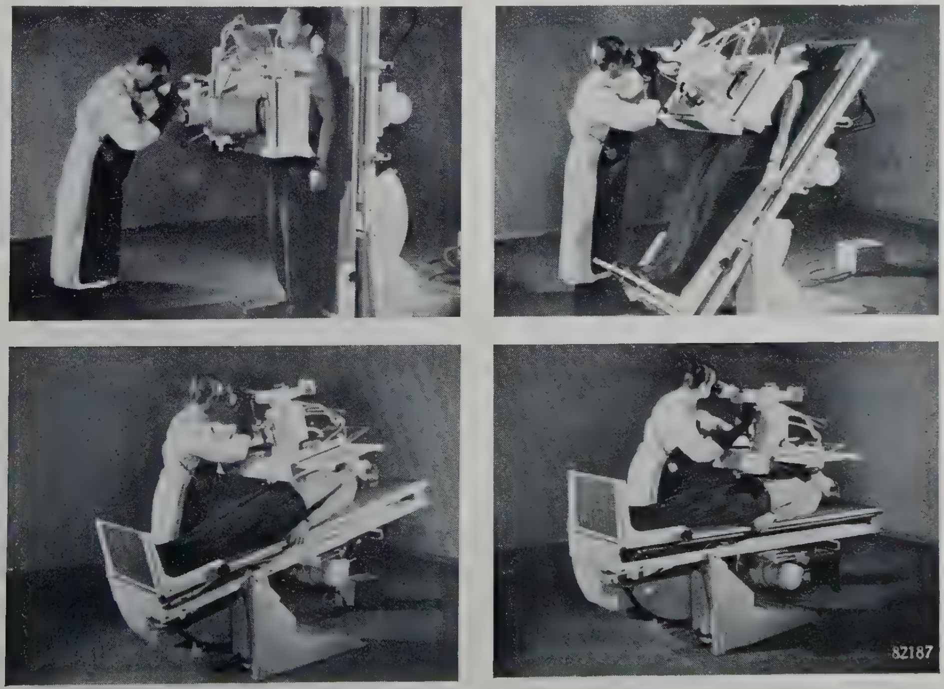

Fig. 3. Using the angled viewing system with the patient in the different positions employed in certain radiological procedures.

the erecting prism Z necessary since without this prism the image would also rotate in the field of view, and would be seen obliquely, or even upside down. Hence it would be difficult to identify the observed image at a glance.

The working of the above-mentioned erecting prism will now be described.

It is well known that the image obtained in a plane mirror is true to nature in all respects apart from the lateral inversion (left-hand and right-hand are reversed). Writing in such a reflected image is from right to left. However, the top and bottom do not change places: we do not see our own reflection upside down in a mirror.

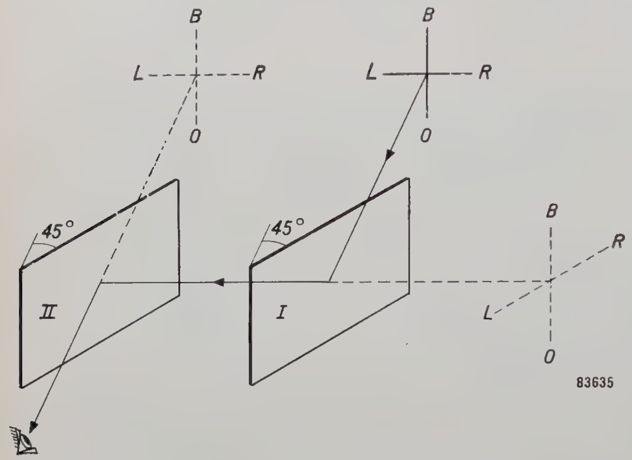

Fig. 4. The reflection at mirror I produces a virtual image in the form of "mirror writing"; it is re-converted to legible writing by reflection at mirror II.

With two parallel plane mirrors, the reversed image in the one is again reversed by reflection in the other, so that any writing in the final image is legible again. The second mirror also leaves the top and bottom of the image unchanged (*fig. 4*).

However, rotating the second mirror about axis X-X', as in the periscope already referred to, produces certain undesirable effects. Suppose that the second mirror is rotated through 90° (*fig. 5*). It then fails to restore the image in the first mirror where L and R are exchanged, to its orginal state; instead, it

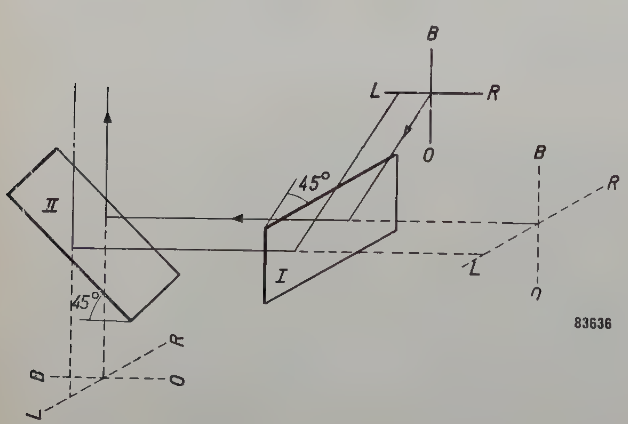

Fig. 5. To an observer standing with his back to us and looking down at mirror II, object $LBRO$ is apparently rotated anticlockwise through 90° in the field of view.

affects only the vertical direction (B-O) of the first reflection and so produces an image in which top and bottom, as well as left and right, are exchanged. The net result is that the image is once more legible, but it is rotated in the field of view through 90° about the direction of view, assuming, that is, that the observer keeps the image in sight during the

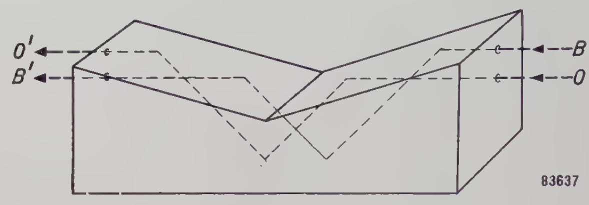

Fig. 6. Prism as described by J. Taylor (Brit. J. Phot. **14**, 348, 1867); it produces three reflections, thus exchanging the top and bottom of the image. If the prism be rotated with an angular velocity ω about direction OB', the image in the field of view will rotate with double this angular velocity, i.e. 2ω.

rotation of the second mirror merely by bending his head forward. (The direction of view as shown in fig. 5 has therefore turned through 90°.)

To compensate for this rotation of the image in the field of view, a prism system Z with three reflecting surfaces is employed (*fig. 6*) [2]). The number of reflections being odd, then, this system (like a single mirror) produces a reversed image. Now, if the prism is rotated through 90° about the axis of the light rays, the whole of the image in the field of view rotates through 180°. Hence the angular velocity of rotation of the observed image is twice that of the prism [3]). To compensate for the above-mentioned rotation of the image in the periscope viewing system, the prism must rotate at half the angular velocity of rotation of the line of sight (E-B).

There is one other point to mention. The image on the viewing screen of the image intensifier tube is inverted. In fig. 2, however, B is erect, because the objective (O) also produces image inversion; two parallel mirrors (S and P) produce no change, and the image rotation is compensated by

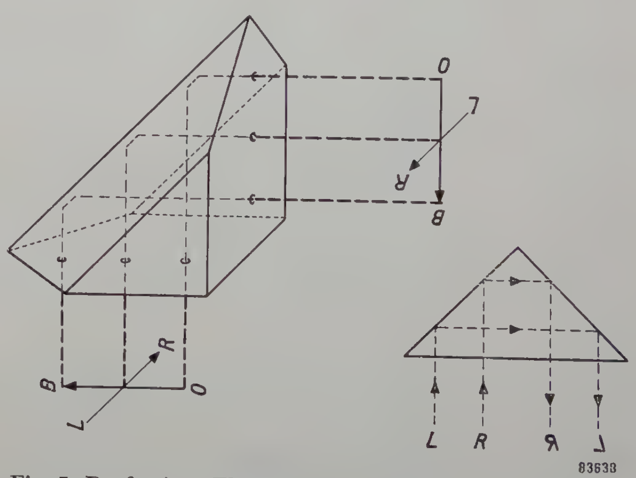

Fig. 7. Roof prism. The 45° prism inverts the image, that is, changes direction B-O; it is seen from the bottom right-hand diagram that a roof prism (two reflecting planes making an angle of 90°) also reverses the image laterally so that L and R are exchanged.

[2]) See Czapski-Eppenstein, Grundzüge der Lehre der Theorie der optischen Instrumente, Barth, Leipzig 1924, 3rd impression, pages 593-599.

[3]) The same effect is obtained as in the rotation of a single plane mirror viewed at a grazing angle.

the rotation of the prism. As already explained, however, the three reflections taking place in prism Z not only rotate, but also reverse the image. To compensate for this reversal, a so-called roof prism (*fig. 7*) is employed at P instead of a simple prism or mirror. Reflection then takes place not at a flat surface (which only exchanges L and R), but at two surfaces at right angles to each other, forming a kind of trough in which B and O are also exchanged. Such a prism produces an erect, legible image, as will be seen from fig. 7. In principle, it would also be possible to place the roof prism at S (fig. 2); however, point P is preferred as a location for this prism because in this case the image to be photographed is also the right way round (see below).

It will be evident from the above that prism Z is shown in fig. 2 rotated 90° from its true position; this is to give a clearer view of the situation.

Constructional details

It will be seen from the preceding explanation of the effect of the erecting prism Z, that when the eyepiece E is rotated about the axis of the periscope X-X', prism Z must rotate with it but at half its angular velocity. Accordingly, the viewing system comprises three individual sections (*fig. 8*) viz:

1) a section (*1*) fixed to the image intensifier tube; it contains the objective O and the roof prism P
2) a section (*2*) adjoining section *1* and rotating about axis X-X'; it contains magnifying lens L and mirror S;
3) a section (*3*) rotating about the same axis X-X', but at only half the angular velocity of section *2*; it contains the erecting prism Z.

The necessary coupling between sections *2* and *3* is obtained by means of a planetary gear drive *4* comprising two toothed rings *5* and *6* (on sections *1* and *2*, respectively) and two bevel gears *7*, whose spindles are carried by section *3*.

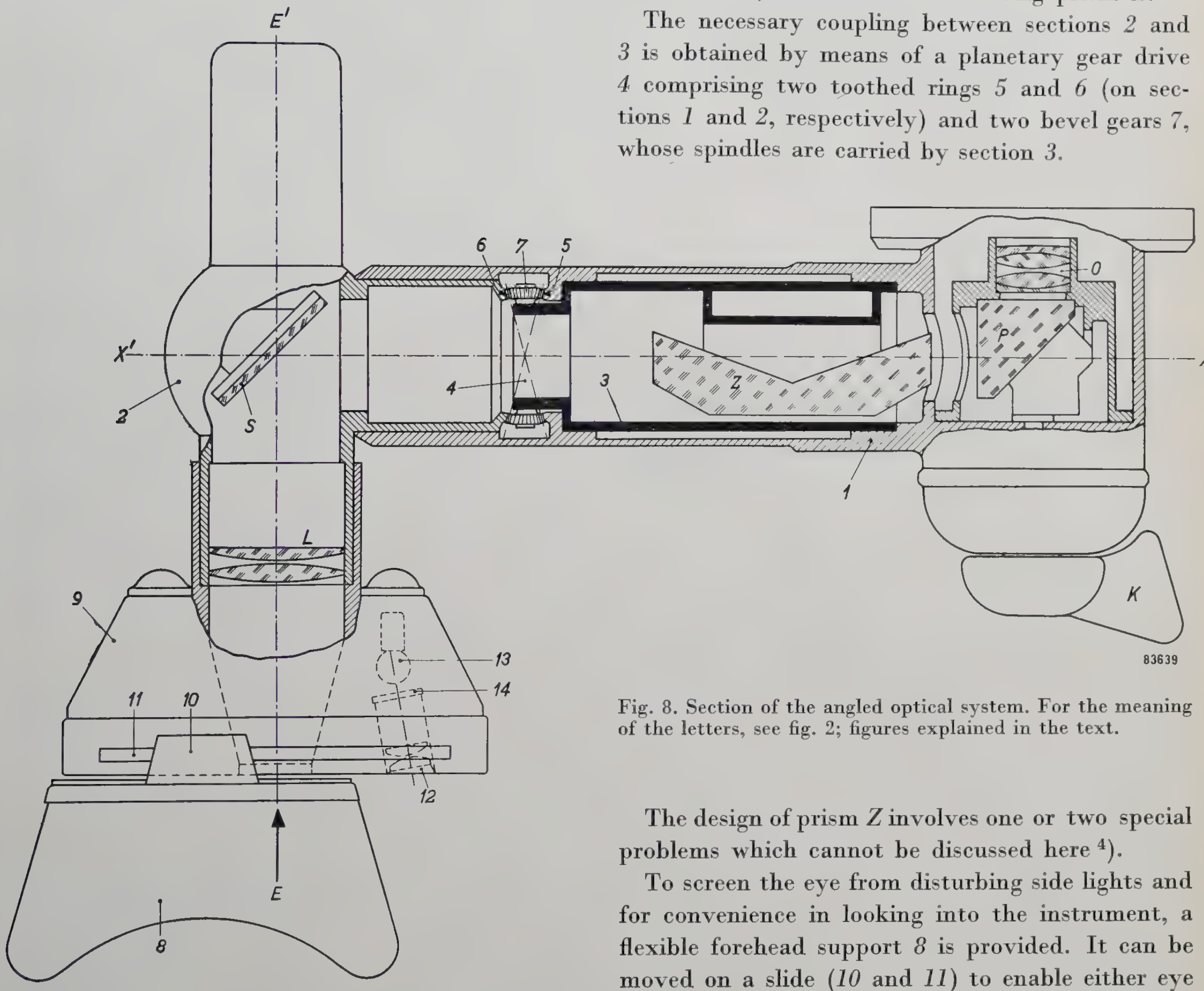

Fig. 8. Section of the angled optical system. For the meaning of the letters, see fig. 2; figures explained in the text.

The design of prism Z involves one or two special problems which cannot be discussed here [4]).

To screen the eye from disturbing side lights and for convenience in looking into the instrument, a flexible forehead support *8* is provided. It can be moved on a slide (*10* and *11*) to enable either eye to be employed. Moreover, section *9* rotates about exis E-E', enabling the observer to tilt his head to any angle.

For the convenience of observers averse to keeping one eye closed, or alternatively staring into darkness, during an examination, small peep-holes (*12*) are provided, one on each side of the eyepiece aperture (E). A lamp (*13*) and a green filter (*14*) behind these peep-holes present to the eye not employed in the examination, a low-luminance

[4]) H. Jensen, Die Abmessungen von Abbe-Umkehr- und Aufrichteprismen, Optik **12**, 150-152, 1955 (No. 3).

field of the same colour as the image in the intensifier [5]).

Photographing the image is a very simple matter, as will be seen from fig. 1. Another tube at right angles to the axis of the periscope, contains the camera (shown on the right in fig. 2). When a photograph is required, prism P is simply turned towards the camera C by means of a knob K, thus deflecting the light from the intensifier through objective O and another lens D on to the film in the camera. Since P is a roof prism, this gives an unreversed image on the film.

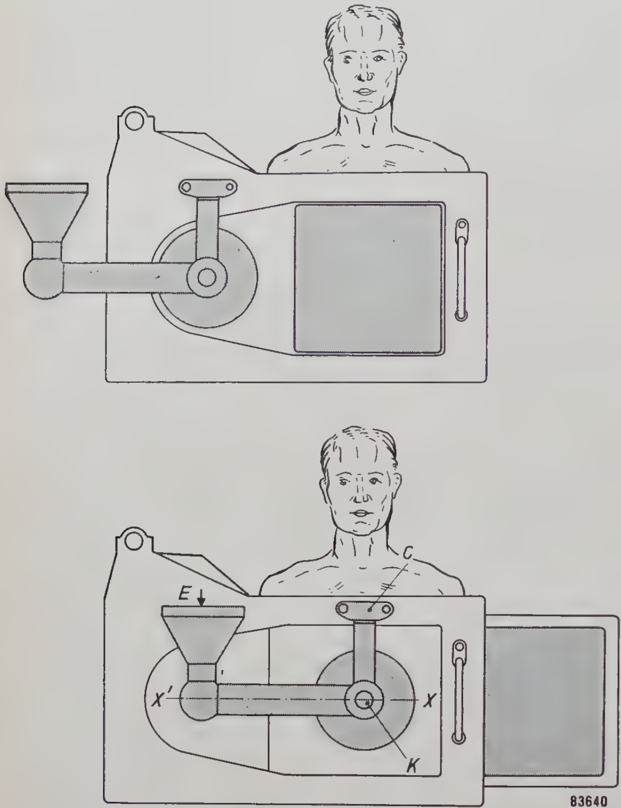

Fig. 9. Top: The apparatus as used with an ordinary fluorescent screen. Bottom: With the image intensifier positioned in front of the patient. For the meaning of the letters see fig. 2 and fig. 8.

The movement of the film and the opening of the shutter are likewise controlled by knob K; it also closes an electric contact to switch the X-ray apparatus from the screening voltage and intensity to the voltage and intensity required for the photograph. Correct exposure is ensured by an electronic time switch incorporated in the apparatus; 35-mm film with a picture-size of 24 × 24 mm is employed in the camera. The camera is equipped with a clockwork film-feed to move 55 frames of film automatically.

The image intensifier itself is mounted on a slide to enable it to be moved aside to introduce an ordinary fluorescent screen into the X-ray beam (*fig. 9*), or for the taking of direct radiographs with ordinary large-size film-casettes as employed in conventional X-ray diagnostic apparatus. The doctor employing the apparatus described here is thus provided at all times with all that he requires for the existing techniques, and with the means of employing image intensification; he can thus compare the two in practice.

[5]) This device was suggested by Prof. H. Schober.

V. MEDICAL ASPECTS OF THE IMAGE INTENSIFIER

by J. FEDDEMA *).

621.386.8: 616-073.75: 621.383.8

In both fluoroscopy and radiography, which may be considered to form the basis of modern X-ray diagnosis, the image intensifier will play a very important part. These two branches of X-ray diagnosis are discussed separately in the present article.

Fluoroscopy

In an X-ray examination the patient is exposed to radiation which is to some extent harmful — a fact which is, fortunately, now better appreciated by doctors employing X-radiation for diagnostic examinations. From the quantitative point of view. fluoroscopy (long exposure at low radiation intensity) produces a very much stronger effect in this respect than radiography (very short, but intense exposure). To reduce the dose required in fluoroscopy as far as possible, the radiologist usually adapts his eyes to a very low luminance level for at least 15 minutes, and to preclude any unnecessary loss of time in re-adapting of the eyes, it is nowadays customary to take all cases requiring fluoroscopic examination one after the other.

In ordinary chest fluoroscopy, involving such adaptation, an X-ray tube current of 2½-5 mA at 60-70 kV is usually employed to ensure an

*) Medical Department of N.V. Philips, Eindhoven.

accurate appraisal of the lung structure. Using the image intensifier, the same result is obtained at the same voltage, but without preliminary adaptation and with a current which need not exceed 0.5 mA. Hence the dose is reduced by a factor of 10. A smaller, but nevertheless appreciable dose-reduction is obtained in the case of relatively thicker and more solid subjects (as in lateral fluoroscopy of the abdominal organs).

Experience has shown that such relatively thick subjects necessitate the use of a scatter grid.

Tests carried out on a "Philite" phantom, as designed by Burger [1]), for a subject thickness corresponding to that of the human thorax have shown that, at the same X-ray tube voltage, fluoroscopy with the image intensifier produces roughly the same contrast-detail perceptibility at 0.1 mA as ordinary fluoroscopy at 4 mA (see II). A tube current of 3 mA is enough to bring the perceptibility of contrast and detail in intensifier fluoroscopy quite a long way towards the standard attained in ordinary, full-size radiographs. Despite the intensifier, however, this standard will never be equalled in fluoroscopy, since the number of X-ray quanta released during the storage time of the eye (0.1-0.2 sec) is invariably very much smaller than the number effective in radiography (see II). Moreover, the high gamma of the photographic emulsion increases the contrast in the radiograph by a factor of $2\frac{1}{2}$ or 3. In fluoroscopy, the actual contrasts are the same with, as without the intensifier, but with it they are raised to a very much higher luminance level. Observers employing the intensifier for the first time are therefore often disappointed, having assumed from the fact that the fluorescent image is seen at virtually the same luminance level as a radiograph examined in front of an ordinary light box, that the two must produce very much the same impression (high contrast).

Photography

The image quality in photography with the image intensifier is limited not only by the blurring effect of the two fluorescent screens, but also by the grain of the film. Since the viewing screen to be photographed is very bright, fine-grain film of low sensitivity may be employed for single photographs. It is found that the X-ray intensity required to take an image intensifier photograph on Kodak "Micro-File" film using a tandem optical system, each component having an aperture ratio of 1 : 1.5, is only from a half to a quarter of that involved in the taking of an ordinary full-size radiograph of the same subject at the same tube-voltage. Also, the high contrast and very fine grain in such a 35-mm photograph results in almost the same information as a normal radiograph.

Comparing image intensifier photography with ordinary screen photography (fluorography) [2]), we find that it has a drawback, viz. the small field of view. On the other hand, it has one or two advantages which should not be underestimated, viz.; the apparatus is relatively small and easy to handle; adjustments prior to taking photographs are readily effected by viewing through the intensifier without any preliminary dark-adaptation; single photographs can be taken on fine-grain 35-mm film giving high contrast and therefore excellent picture-quality: all these advantages are procured with an X-ray dose at least a factor of 3 smaller than that required in ordinary radiography, instead of 3 or 4 times larger as in fluorography.

Cinematography

To all appearances, cinematography with the image intensifier will find a great deal of scope in the future. It is the only method of photographing transient processes in the human body without risk either to the subject (overdose) or to the X-ray tube (overloading). For this purpose, a more sensitive 35-mm film, e.g. Gevaert "Orthoscopix" or Agfa "Fluorapid", is employed. Experience has shown that the dose required to expose a single photograph on such film is less than 1/10 of the dose ordinarily employed in radiography: this at once implies the possibility of cinematography. Several films taken with the image intensifier are already available. Equipment for this type of cinematography is shown in *fig. 1;* for particulars see *Table I* [3]).

Table I. Examples of films made with the image intensifier.

1) Deglutition at larynx level, in lateral projection. 80 kV, 10 mA, 20 frames/sec, duration 15 seconds. 6 m of film, with a total dose of roughly 2 r.
2) Film in frontal projection of the bulbus (entrance of the duodenum). 120 kV, 11 mA, 8 frames/sec., duration 2 minutes. 20 m of film, with a total dose of 50 r.
3) Micturition. 125 kV, 20 mA, 8 frames/sec., duration 56 sec. 10 m of film, with a total dose of 45 r.
4) Cerebral angiography (examination of blood vessels in the brain) in lateral projection. 90 kV, 10 mA, 16 frames/sec, duration 20 sec. 7 m of film, with a total dose smaller than 5 r.

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1) Philips tech. Rev. **11**, 291-298, 1949/50.

2) See for example, Philips tech. Rev. **13**, 269-281, 1951/52.

3) These experiments were carried out in collaboration with J. van der Wal and J. Proper of the Research Laboratories at Eindhoven.

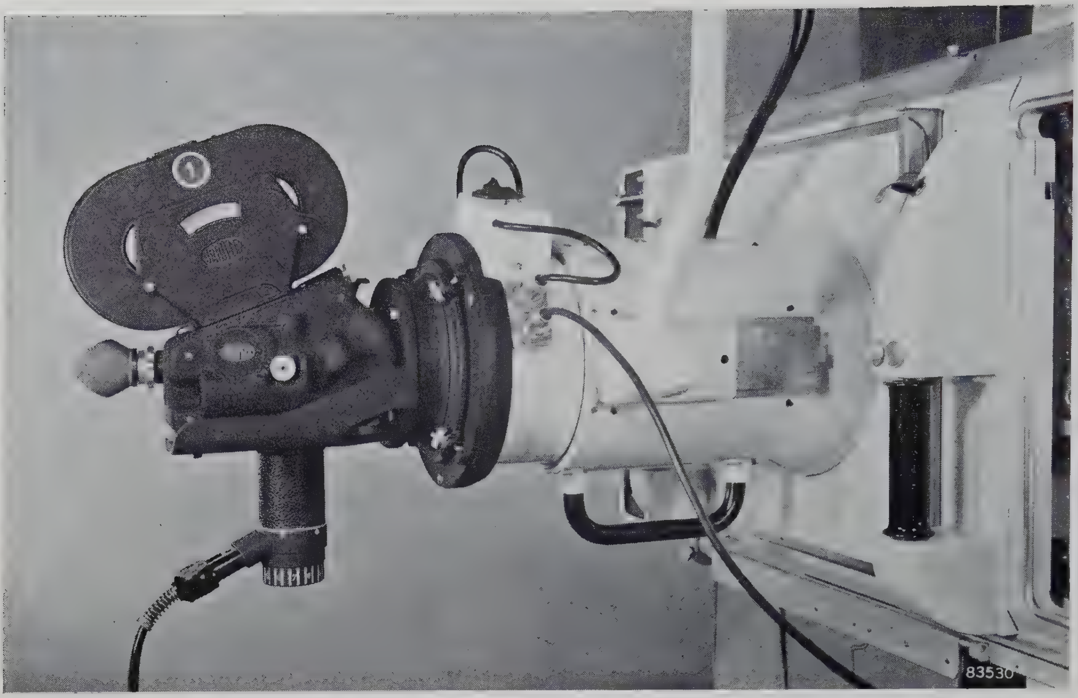

Fig. 1. Apparatus for cinematography with the image intensifier. Right: Viewing system on the stand of an ordinary diagnostic X-ray installation. The usual fluorescent screen is replaced by an image intensifier. Left: The film camera, with the film magazine on top; an eyepiece to view the image during the taking of the film is at extreme left, on the axis of the camera and image intensifier (see III).

Most of these films were made with an X-ray tube having a 0.3 mm focus, without overloading it. For each of them the distance from focus to screen was 90 cm, since a scatter grid designed for this distance was employed.

Table II. Dose to patient in different methods of gastric radiography (object thickness 21 cm). All exposures with 3-phase full-wave rectification, 120 kV, 1 mm Al-filter, conventional scatter grid, focus-screen distance 100 cm.

Method	Dose in r
Ordinary radiography	0.5
Miniature radiography with mirror camera .	
a) Single exposures	
Gevaert "Ortho Scopix"	2.5
Same film 2 × magnification	10
b) Serial exposures on 70-mm film	
5 frames per sec for 1 sec	12.5
5 frames per sec for 10 sec	125
c) Cinematography on 35-mm film	
20 frames per sec for 1 sec	35
20 frames per sec for 1 minute	2000
Image intensifier photography with tandem lens system	
a) Single exposures	
Gevaert "Ortho Scopix"	0.05
Kodak "Micro-File"	0.75
b) Cinematography on 35-mm film Gevaert "Ortho Scopix" or Agfa "Fluorapid", 8 frames per sec for 2 min; overall length of film 20 m, total number of frames on film 1000.	
Total dose	50

Although it is already evident from this table that the dose itself is a more or less minor problem in X-ray cinematography with the image intensifier, this all the more evident from *Table II*, indicating the dose to the subject in different methods of gastric radiography.

Methods of diagnostic exmination

To show in how far it is practicable to employ the image intensifier in the various methods of diagnostic X-ray examination, a general survey of these methods will now be given.

Examination of the skeleton and the joints of the limbs

Because of the importance of minor changes in the bone structure in skeletal examinations, ordinary radiography is still the only effective method. Here, then, the image intensifier cannot supersede the radiograph, although it is very useful in exploratory examination before the actual exposure. Such visual examination facilitates the correct positioning of the object (say, for the projection of joint spaces and small calcifications). Image intensifier fluoroscopy is also useful for locating foreign bodies and for the examination of joints into which contrast medium, or air, has been injected.

Again, the image intensifier is ideal for follow-through examinations to ensure, for example, that the re-setting of bone fractures, dislocations, etc has been satisfactory. It is in examinations of this kind that the danger from radiation has so often been underestimated, and many a doctor has injured his fingers or hands in the course of them. The same applies to the pinning of fractures, that is, driving a stainless metal pin through the shaft of a broken bone. It is now possible to make sure, by a check examination in the operating theatre itself, that the pin has been driven into the precise position selected for it this eliminates the often enervating delay whilst radiographs are developed, and also cuts down the overall operating time.

Examination of the spinal column

Although it is now possible to obtain a fairly accurate impression of possible defects in the spinal column, especially in the region of the cervical vertebrae, with the aid of the image intensifier, the ordinary radiograph is still the obvious choice for such examinations, at any rate for the time being, because it enables the bone structure to be assessed correctly. However, there is scope for the image intensifier in myelography, in which a certain amount of contrast medium is injected into the canal of the spinal cord and any obstructions preventing the passage of this medium are located by examining the subject in different positions. Not only the possibility of working in daylight, but also the small X-ray dose to the patient is important in such examinations, since abnormalities of this kind usually occur in the lumbar region, where the proximity of the genitals, extremely sensitive to radiation, necessitates more than ordinarily careful dose control.

Examination of the skull

A simple X-ray apparatus may be very valuable in the consulting room of an ear, nose and throat specialist, say, as a means of examining an inflammation of the nasal sinuses, visible either by a swelling of the mucous membrane, or by an accumulation of fluid in the sinuses. The present field of view of the image intensifier, viz. $13\frac{1}{2}$ cm, is ample to enable such a condition to be diagnosed at a glance (*fig. 2*). Also, X-ray cinematography of the jaw joint may well be useful to the specialist.

Again, cinematography may be employed in cerebral angiography, that is, studying the circulation in the blood vessels of the brain by injecting contrast medium into the carotid artery.

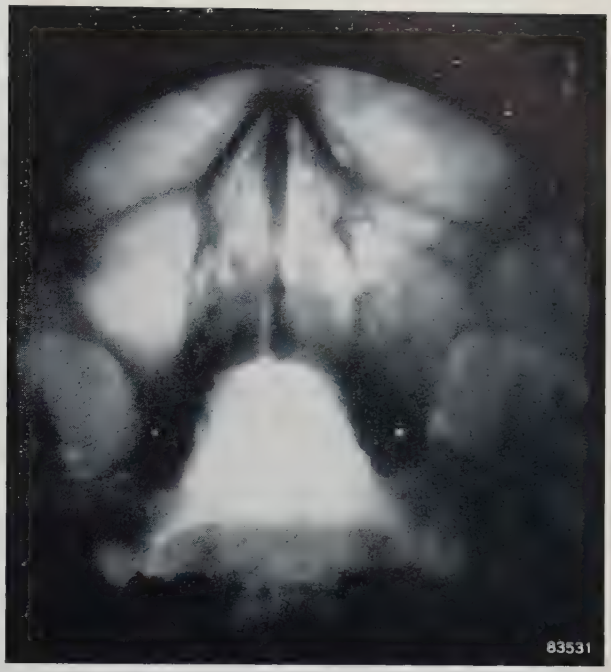

Fig. 2. Reproduction of a still photograph taken with the image intensifier. It shows the nasal sinuses in the upper jaw.

Examination of the digestive organs

Because food passes very quickly through the upper portion of the oesophagus, there has been for many years now a desire to record the movements of the larynx, etc. cinematographically. Holmgren accomplished this in Sweden as early as 1946 by means of screen cinematography. However, image intensifier cinematography offers very much better opportunities in this respect by enabling a higher frame frequency to be employed (*fig. 3*). Since the passage of food through the lower portion of the oesophagus, and through the stomach and the small intestine, is much slower, cinematography of these regions is not essential; however, image intensifier screening of these organs is very useful. Films showing the movements of the stomach and intestines are undoubtedly spectacular, and eminently suitable for purposes of instruction.

Examination of the kidneys and genitals

A clear view of the kidney and pelves (filled with contrast medium) and their contractions is readily obtained by fluoroscopy with the image intensifier. In retrograde pyelography, in which the contrast medium is injected through the urinary ducts, the above-mentioned movements can be easily followed.

Cystography usually involves taking single still photographs of the bladder during micturition. Image intensifier cinematography may be employed for this purpose in the future. Owing to the proxi-

mity of the genitals it is necessary to employ only a very small dose of radiation in this examination. This is also the case in hysterosalpingography in which contrast medium is injected into the uterus, usually to ascertain whether the oviducts are clear of obstruction. The insertion and manipulation of instruments can invariably be observed in daylight.

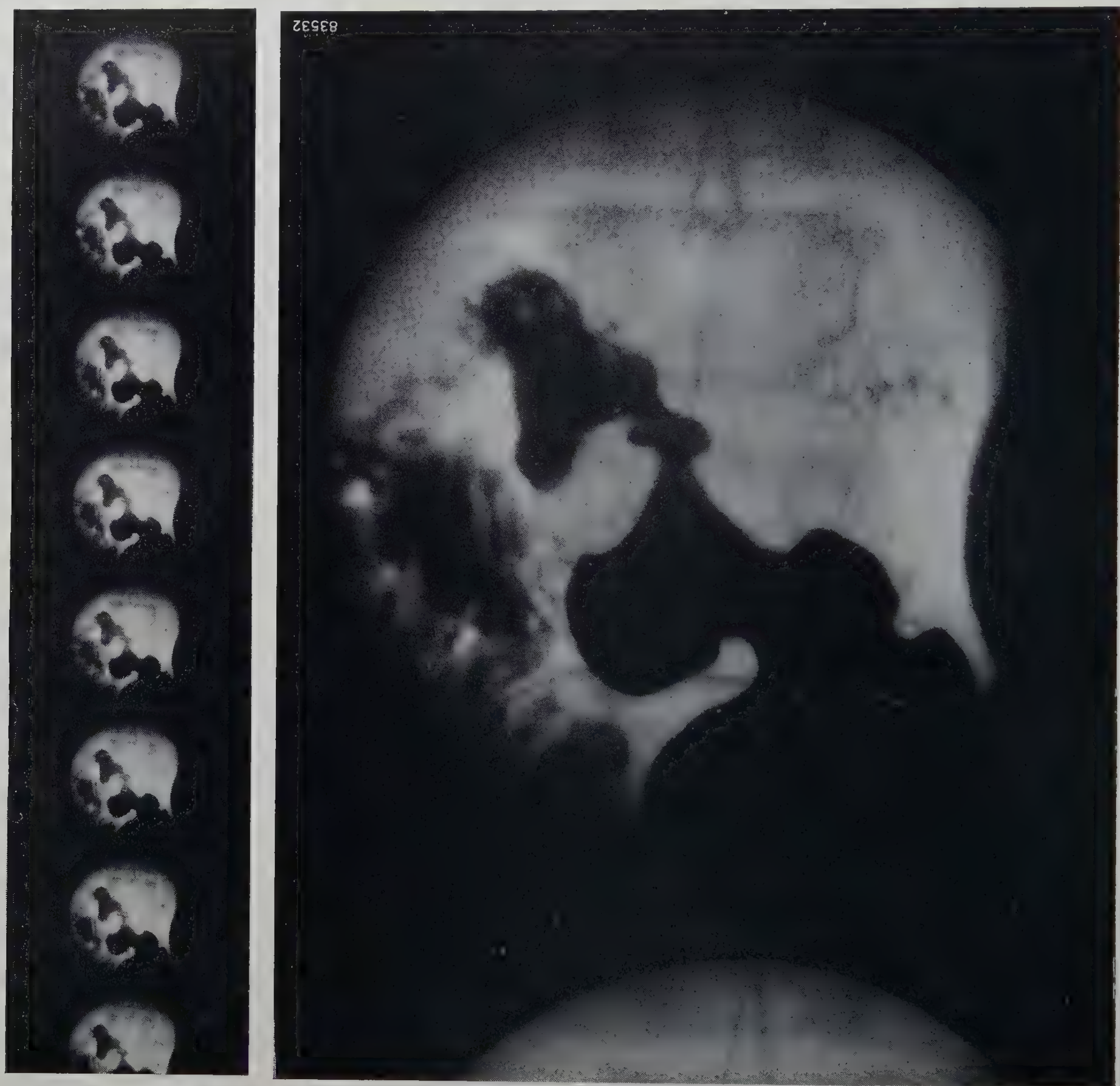

Fig. 3. Gastric cinematography. Left: Part of the film strip. Right: Enlargement of one frame in this strip.

X-ray examination during pregnancy should be kept to a minimum: it is necessary only in some cases during the final weeks, to show the position of the foetus or pelvic anomalies, etc. Here, ordinary radiography is still the best method.

Examination of the lungs and respiratory passages

In serial chest-fluoroscopy the time required for adaptation is virtually immaterial; the use of the image intensifier for this purpose is therefore precluded, at any rate for the time being, by its small field of view. However, the intensifier may well be employed for exploratory examinations of individual subjects; it also deserves consideration as a means of examining local disorders, in view of the high contrast-detail perception in the image. Shadow-producing foreign bodies in the respiratory system are readily located; moreover, image intensifier fluoroscopy is ideal as a means of observing the position of such objects in relation to the instruments inserted to remove them.

Examination of the heart

In heart-catheterisation, the image intensifier enables the X-ray dose employed during the insertion of the catheter, which sometimes takes a very long time, to be reduced considerably.

Cinematography merits consideration as a means of examining highly localised disorders of the heart and adjacent blood vessels.

Whereas the field of view is not large enough to permit of a total examination of the heart in adults, the study of the heart function in children by means of the intensifier has already produced some remarkable results.

Although this summary is by no means complete, the examples given in it show clearly enough the potentialities of the X-ray image intensifier as an aid to medical diagnosis.

VI. INDUSTRIAL RADIOLOGY WITH THE IMAGE INTENSIFIER

by G. LANG *) and R. O. SCHUMACHER *). 620.179.1:621.386.8:621.303.8

Industrial radiology is now a widely used method for examining materials; in fact, it is one of the most important and reliable of the non-destructive methods of inspection. In the light metals industry, for example, X-rays are employed on a large scale for examining castings for defects fluoroscopically. The relatively low absorptive power of light metal alloys enables X-ray shadow pictures of adequate luminance to be obtained. With an X-ray tube of small focus (e.g. 0.4 × 0.4 mm) an enlarged shadow image can be projected [1]), giving unusually good detail-perception.

The situation with regard to the examination of steel, however, is less favourable. The welding of parts normally subjected to heavy loads, for example, parts of boilers, tanks, bridges, ships, etc., usually rests upon a reliable, non-destructive method of inspection enabling the quality of the welds to be properly assessed. Because of the high absorptive power of the iron, however, steel contructional elements cannot usually be examined fluoroscopically; such X-ray shadow pictures are very faint and can therefore be observed only in a darkened room after the eyes have been thoroughly dark-adapted. In many cases, where the particular constructional elements are either too large or too heavy to be conveyed to a screening room, fluoroscopic examination is out of the question for this reason alone. Moreover, fluorescent images of steel parts afford only limited perceptibility of detail; to ensure adequate screen luminance it is necessary to employ thick, coarse-grained fluorescent screens and also high-powered X-ray tubes which preclude all possibility of a small focus. In practice, then, steel is suitable for fluoroscopic examination only if not more than 6 or 8 mm thick. Since in most welded constructions the material to be examined is very much thicker, it has hitherto been impossible to make such X-ray examinations other than by the photographic method, which, however, is time-consuming and expensive.

Fig. 1. Industrial radiology equipment using the image intensifier, for experiments and demonstrations. Note the beam exit aperture of the X-ray tube, radiating vertically upwards, behind the lead glass window. Above it is the work to be examined, in this case a welded Y-joint.. The image intensifier, mounted in a box on top of the apparatus, is provided with an angled optical system. The two handles seen on the left of the apparatus, are manipulated by the observer to locate the work as required.

*) C. H. F. Müller Aktiengesellschaft, Hamburg.

[1]) See G. C. E. Burger, B. Combée and J. H. van der Tuuk, X-ray fluoroscopy with enlarged image, Philips tech. Rev. **8**, 321-329, 1946.

It will be evident that the appreciable increase in luminance given by means of the image intensifier reduces or even eliminates the above-mentioned objections to the use of fluoroscopy for examining steel. X-ray examination as applied to industrial production has thus acquired new possibilities, which have been investigated in the application laboratory of C.H.F. Müller in Hamburg. A brief account of the results of this investigation will now be given [2]).

either direct from the viewing screen of the image intensifier by means of a camera attached to the viewing system, or in the usual way on film or X-ray paper in a casette exposed in front of the intensifier.

The experiments described here were carried out on steel plates and tubes of different thicknesses. A measure of the possible detail-perception was obtained by means of the DIN test objects employed in ordinary radiography; such a test object (penetrameter), secured to the side of the object facing the X-ray tube, contains a series of wires of progressively increasing thickness, of the same material as the work being examined. If the diameter of the thinnest wire just discernible by the observer is, say, 3% of the thickness of the material screened, then it is said that the *wire-sensitivity* is 3%, which is taken as an indication of the image quality [3]).

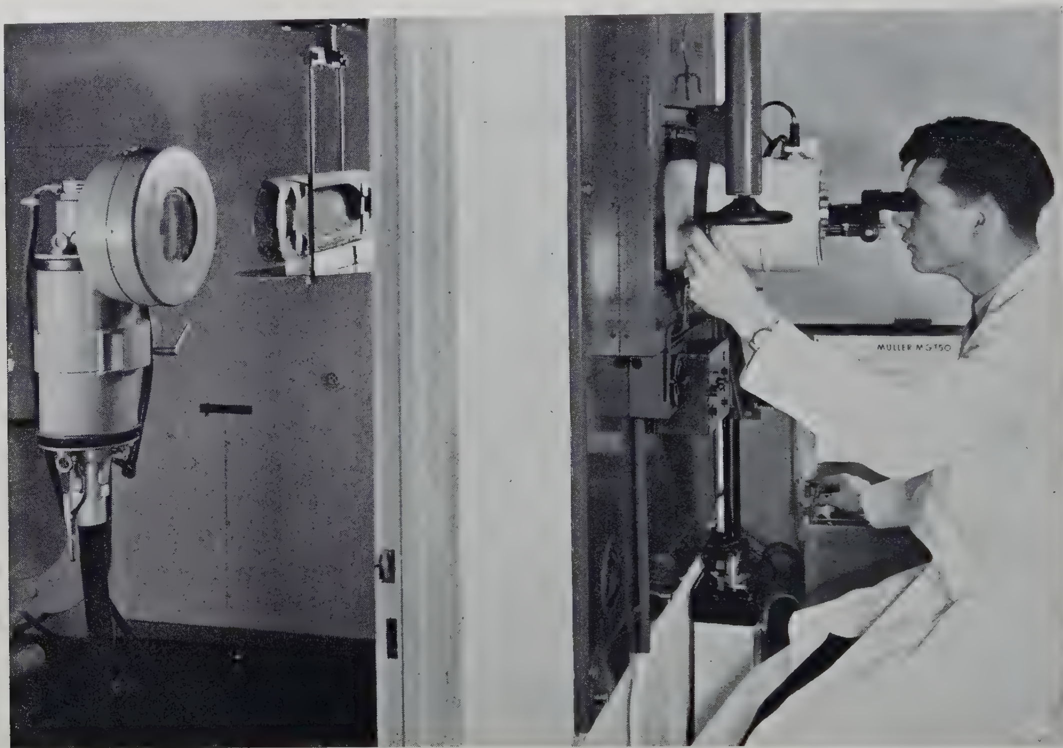

Fig. 2. Viewing equipment with built-in image intensifier. Here, the viewing optical system is a binocular microscope.

The experimental installations employed in the investigation are shown in *fig. 1* and *fig. 2;* the one incorporates an angled optical system as described in article IV of this series, and the other a binocular microscope (see article III). We consider a binocular system most suitable for the examination of materials because over long working periods it is less fatiguing to view with both eyes than with one. Defects revealed by fluoroscopy can be photographed for more accurate appraisal, or for test records,

Curves showing the image quality so determined, plotted against the material thickness, are shown in *fig. 3*. X-ray tube voltages between 80 kV (for steel roughly 2 mm thick) and 150 kV (for steel

[2]) See R. Lang, Röntgendurchleuchtungseinrichtung mit Bildverstärker, Energie und Technik **5**, 163, 1954 (July). The arrangement described in this article, as shown in fig. 1, was demonstrated at various exhibitions last year.
Investigations into the examination of materials with the X-ray image intensifier have also been carried out in the laboratories of the Philips factories at Balham (England); see A. Nemet and W. F. Cox, Intensification of the X-ray image in industrial radiology, to be published in Proc. Instn. Electr. Engrs. **A 103**, 1956.

[3]) The wire-sensitivity is not an exact measure of the lateral dimensions of the smallest perceptible defect, since they are also governed by the shape and nature of the defect (gas occlusions, slag, cracks, and so on). Similarly, in comparing the fluoroscopic and photographic methods for image quality, the wire-resolution can be taken only as a rough indication, since conditions vary considerably between different observations.

roughly 20 mm thick) were employed in the observations; the viewing was carried out in daylight. A 0.4 × 0.4 mm focus was employed.

The increase in the smallest perceptible wire diameter with the thickness of the material screened is not proportional to the latter, but more gradual

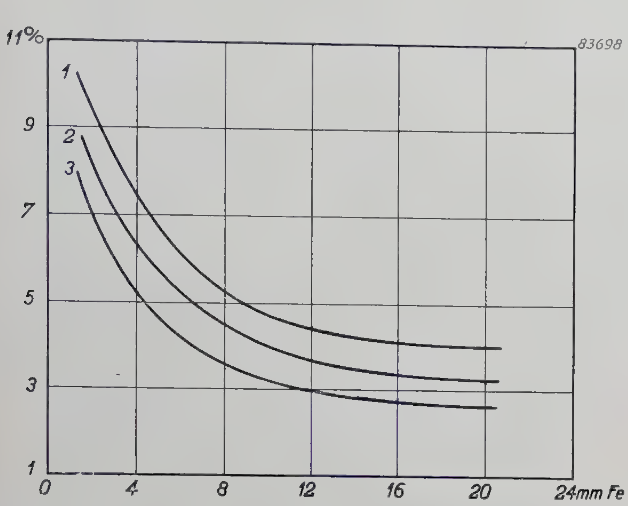

Fig. 3. Wire-sensitivity (in % of thickness of object) in the fluoroscopy of steel with an X-ray image intensifier, plotted against the thickness of the material (in mm). Tube voltage 80 to 150 kV, distance between focus and intensifier 50 cm, size of focus 0.4 × 0.4 mm. Enlarged X-ray shadow picture projection: the magnifications associated with curves *1*, *2* and *3* are 1.2, 1.6 and 2.2, respectively.

(in curve *1*, for example, this diameter is 0.3 mm for 4 mm Fe, and increases only to 0.8 mm for 20 mm Fe). The consequent improvement in image quality, expressed as a percentage, with increasing material thickness, as demonstrated in fig. 3, is analogous to what is found in ordinary fluoroscopy[4]). Experience has shown that for materials thicker than 10 mm, the most important in practice, the wire-sensitivity attainable with the image intensifier is 3%. This may be compared with direct examination with an ordinary fluorescent screen (which, as we have already seen, is possible only in the dark and with steel not thicker than 8 mm, and imposes a very much heavier voltage and power load on the X-ray tube), in which the wire-sensitivity is at best 6%.

The wire-sensitivity of 3% obtained in fluoroscopy with the image intensifier is ample for most purposes. Even better image quality, to roughly 1%, is obtained in photographic X-ray examination. In many cases, however, such a high degree of detail-perceptibility is unnecessary, and in such cases X-ray examination has hitherto been dispensed with in view of the above-mentioned disadvantages of the photographic method. It is probable that the simplicity and efficiency of fluoroscopy with the image intensifier will now cause this method to be adopted also in the steel industry. An additional feature of such fluoroscopy is that by virtue of the relatively low X-ray intensities employed, one or two simple precautions are sufficient to ensure that the operators are fully protected against radiation hazard.

The above-mentioned results are valid for a normal distance between focus and intensifier, e.g. 50 cm. This relatively long distance enables an enlarged X-ray shadow picture to be projected; the advantage of such projection, long employed in the radiology of light metals, is demonstrated by curves *2* and *3* of fig. 3. In the screening of relatively thicker materials, the quality of the image may be likewise improved by reducing the focus-to-intensifier distance, and so increasing the luminance of the screen (placing the intensifier near the object instead of projecting an enlarged image). Reducing this distance to roughly 20 cm (a closer approach to the focus is impossible owing to the shield round the X-ray tube) enables steel up to 30 mm thick to be screened, with an image quality of roughly 3%. Tests at the same distance with a larger focus and higher tube power have shown that it is even possible to screen steel 40 mm thick, although the image quality then deteriorates to some extent.

It is necessary to take steps to ensure that no unfiltered, primary radiation strikes the fluorescent screen of the image intensifier, since the dazzling brightness produced by such radiation at some points on the viewing screen and the associated afterglow impair the overall image quality.

When thick steel is examined a slightly unsteady image is obtained ("noise"), owing to the fact that by selective absorption in the steel, the X-rays are attenuated and only the shorter wavelengths remain; hence the image is built up from only a small number of large quanta (see article II). This effect does not seriously affect the image quality, however.

To conclude this brief article one or two cases from practical experience in the radiology of steel with the image intensifier will now be discussed.

To our knowledge, the image intensifier was first employed industrially to determine the level of liquid in steel bottles; with a tube voltage of 130 kV and a tube current of 6 mA, it is possible to observe the liquid level direct on the viewing

[4]) This effect is attributable to the fact that the geometrical blurring and the blurring of the image caused by the fluorescent screen, which impose a limit on the wire-resolution in the case of thin wires (thin walls), do so less noticeably with thick wires (thick walls). Although the amount of X-radiation scattered in the material increases at the same time, thus reducing the contrast, the first-mentioned factor evidently predominates.

screen of the image intensifier in daylight. The overall thickness of material thus viewed was 6 mm, but laboratory tests have shown that the same process can be applied to steel bottles with a wall-thickness of 6 mm, i.e. an overall steel thickness of 12 mm.

Another promising application of the image intensifier is in the inspection of bearings. *Fig. 4* shows a fluorograph (on miniature film) of a defect, detected visually with the aid of the image intensifier, in a bearing 13 mm thick. *Fig. 5* (likewise on miniature film) shows defects similarly detected in a welded seam in sheet steel 15 mm thick. In accordance with expectation (see article II of this series), the quality of these miniature photographs is better than that of the visual image referred to in fig. 3.

It is also possible to foresee important uses for fluoroscopy with the X-ray image intensifier in the inspection of pipes with welded longitudinal seams, as employed in long distance gas and water mains and oil pipe lines. In these mass-produced pipes we have a typical example of inspection being dispensed with altogether hitherto, because photographic X-ray examination was too expensive. A possible arrangement for screening such pipes,

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Fig. 5. Welded seam in steel sheet 15 mm thick, photographed with the image intensifier. Note the faultsin the seam, and the shadow of the DIN test-object placed in front of the plate. X-ray tube data: 140 kV, 3 mA; focus 0.4 × 0.4 mm. Exposure 15 seconds.

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Fig. 4. Photograph made with the image intensifier of one half of a bearing block: the radiation penetrated 10 mm of steel plus 3 mm of bearing bronze. The segregation of lead can be cleasly seen. Tube data: 150 kV, 3 mA; focus 0.4 × 0.4 mm. Exposure 20 seconds.

generally between 8 and 10 metres long, is as follows. The X-ray tube is secured to a long arm inserted into the pipe and radiates outwards through the welded seam towards the image intensifier. The pipe is moved parallel to its axis in such a way that the seam remains between the stationary intensifier and the X-ray tube. Employing such an arrangement it is possible to work comfortably with a distance of no more than 20 cm between focus and image intensifier. Provisional tests have shown that seams can be examined continuously at the rate of roughly 5 cm per second.

A similar method could be employed to examine longitudinally welded steel girders.

Summary I-VI. The first of the articles (I) in this series on the application of the X-ray image intensifier deals with the actual operation of the intensifier tube. In this tube, the luminance of the X-ray shadow picture on the fluorescent screen is intensified between 800 and 1200 times. This luminance intensification may be employed both to give better viewing conditions for the eye and to reduce the required X-ray intensity. As explained in article II, however, it is not advisable to reduce the intensity too far, since undue reduction causes the fluctuations in the number of X-ray quanta to become visible, which affects the observation of detail. By a quantitative comparison of fluoroscopy, with and without the image intensifier, direct radiography, fluorography, and photography with the image intensifier, it is shown that under practical conditions, say, in fluoroscopy, the perception of detail is governed almost entirely by the fluctuations, whereas in direct radiography and image intensifier photography on fine-grain film this is not the case.

Article III discusses the various optical devices which can be employed to enlarge the reduced image on the screen of the image intensifier tube without any appreciable loss of luminance to the observer; optical systems for photography and cinematography are also discussed. Detailed descriptions are given of the following: a binocular microscope for fluoroscopy; an angled microscope with a large exit pupil readily located by means of a movable, frosted glass viewing plate; a tandem lens system comprising two conventional fast photographic objectives, for photographing the small viewing screen (15 mm in diameter) of the image intensifier on miniature film. Article IV describes an angled viewing optical system enabling the intensifier to be used for X-ray diagnosis with an ordinary, universal examination table. Here, a rotatable eyepiece enables the radiologist to observe the X-ray image in a normal position, and without any image-rotation when tilting the patient.

Finally, the practical application of the intensifier is discussed in the last two articles (V, VI). It is shown that the limited

field of view of the tube is not necessarily a handicap either in medical examinations or in industrial radiology. As regards medical applications, article V contains a survey of the parts of the body and organic functions the examination of which is facilitated by the use of the image intensifier. Points emphasized are the value of the intensifier in examinations involving the use of contrast media, and the development of X-ray cinematography, whose practical possibilities can be fully exploited only with the aid of the intensifier. The article contains one or two examples of X-ray films already made, including one of the duodenum; the subject dose employed in the taking of this 2-minute film (roughly 1000 frames) is only 50 r. An investigation into the industrial possibilities of the image intensifier (article VI) shows, amongst other things, that steel constructional elements 20 mm thick can be examined readily in daylight, the smallest perceptible detail then being 3% of the material thickness. Where the detail is larger, it is even possible to examine steelwork 40 mm thick.

A TECHNIQUE FOR MACHINING TUNGSTEN

by R. LEVI *).

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Developed primarily for the manufacture of "dispenser" type cathodes, the technique for machining tungsten described in this article may well prove valuable for other applications of tungsten metal.

Tungsten metal plays an all-important part as filament material in incandescent lamps because of its very high melting point (about 3400 °C) and its low vapour pressure and high strength at elevated temperatures. For similar and other reasons, the metal is extensively used in X-ray tubes, both for anodes and cathodes, and for relay contacts, etc. Undoubtedly its physical properties would make tungsten ideally suited for many more applications in the laboratory and in industry, but its potential usefulness has been limited by its almost complete lack of machinability; pure tungsten is very hard and brittle at normal temperatures so that it is virtually impossible by normal methods to fabricate tungsten parts of intricate shapes and close tolerances.

A new technique, developed in the Philips Laboratories at Irvington during recent years and to be described in this article, has opened a new approach to this problem and holds good promise for future applications of tungsten.

When it was first attempted to use tungsten for incandescent lamp filaments, the very fact of its high melting point necessitated the application of unusual manufacturing methods (powder metallurgy). The present-day technique for making tungsten filaments may be briefly summarized as follows [1]). Tungsten powder of a suitable grain-size distribution and other characteristics, obtained by chemical processes, is pressed into bars at a pressure of 6-25 tons per square inch (1000-4000 kg/cm^2) and heated in an oven to a temperature of say 1100 °C. Under such treatment (pre-sintering) the metal grains are bonded together to a certain extent and the bars acquire sufficient strength to permit subsequent handling in the sintering process proper. This consists in heating the pre-sintered bars in a hydrogen atmosphere by an electric current to a temperature of about 3000 °C. Sintering of the tungsten metal grains under these conditions occurs to such an extent that the density of the material, which in the pre-sintered bars may have been about 55% of the value for solid tungsten, may rise to more than 90%. The density of the sintered bars is further increased by passing them a number of times in a hot state through a hammering or swaging machine. This process results in rods a few millimeters in diameter which, in the hot state, are sufficiently ductile for drawing into wire. Tungsten wire of diameter 1 mm down to 0.01 mm or even less is currently produced in this way, and coiled for filaments.

Apart from this highly developed and mechanized technique of drawing tungsten wire, machining possibilities for the very hard sintered tungsten ingots (or rods and sheets obtained from them) at normal temperatures are restricted to grinding and slicing by means of silicon carbide cut-off wheels [2]). Such a procedure can obviously be useful only for simple parts of convenient dimensions. Attempts to form the parts *before* the final sintering operation, either by pressing the tungsten powder in a die or by machining pre-sintered bars (density about 55%) have not been very successful. Machining of the

*) Philips Laboratories, Irvington-on-Hudson, N.Y., U.S.A.

1) C. J. Smithells, Tungsten, Chapman & Hall, London 1945, 2nd ed.; see also J. D. Fast, The preparation of metals in a compact form by pressing and sintering, Philips tech. Rev. 4, 309-316, 1939.

2) For hot machining methods see D. White and J. J. Aust, Materials and Methods 27, 81, 1948.

very porous pre-sintered bars does not yield smooth surfaces since the particles are torn out in clusters rather than cut. Moreover, considerable shrinkage and warping generally occur during the final sintering process, making it very difficult to attain the required shape and dimensions.

The technique to be dealt with in this article [3]) was specially developed for applications of tungsten in which a certain accurately controlled *porosity* of the metal is an essential condition, viz., the Philips "dispenser" cathodes (the L-cathode, described in this Review some years ago[4]), and its more recent "impregnated" version which will be described in these pages shortly [5])). Basically the technique consists in the following steps. A porous ingot of tungsten already sintered to the required degree is first *infiltrated* with a suitable molten metal which does not react with the tungsten in any way. The impregnated tungsten body can then be machined at normal temperatures with conventional carbide or high speed steel tools. Finally the infiltrant is removed by volatilization and a precisely machined pure tungsten part is thus obtained, with porosity restored to the exact value established during the sintering operation.

Fig. 1 illustrates the appearance of a tungsten part in various stages of the process. Copper was used as the infiltrant in this case. Owing to subsequent oxidation of the copper at the surface, the machined part will exhibit only a slight difference in colour before and after volatilization; these two stages therefore are not shown separately in the photograph.

Fig. 1. Steps in machining a tungsten part according to the new method. From bottom to top: Pre-sintered tungsten bar (density 55% of the value for solid tungsten); tungsten bar sintered to the required density (83%); sintered tungsten bar after impregnation with copper; part machined by normal operations from the impregnated bar. The copper is volatilized after machining; this process does not affect the dimensions and restores the density precisely to its original value of 83%.

It should be pointed out that the infiltration of porous tungsten bodies with metals such as copper or silver has been known for many years and has been applied for making spot-welding electrodes and certain types of electrical relay contacts. Such contacts must primarily possess a good electrical conductivity, the imbued copper or silver contributing to this end, while the role of the tungsten is to prevent the contact from sticking or being welded together by the effect of arcing. The purpose of the infiltration in our case being quite different, the requirements to be met will obviously be quite different too. This is seen most clearly in the selection of the infiltrating metal. In both cases the molten infiltrant must satisfy the condition of

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[3]) R. Levi, U.S. Patent No. 2 669 008, Feb. 16, 1954. See also R. Levi, The machining of tungsten and its application in the fabrication of Philips dispenser cathodes, Convention record of the I.R.E. 1954 National Convention, part 3, 70-73.

[4]) H. J. Lemmens, M. J. Jansen and R. Loosjes, A new thermionic cathode for heavy loads, Philips tech. Rev. **11**, 341-350, 1949/50.

[5]) R. Levi, J. appl. Phys. **24**, 233, 1953; Le Vide **9**, 284-289, Nov. 1954; J. appl. Phys. **26**, 639, 1955 (May).

wetting the tungsten and of penetrating the porous body by capillary action. For the machining technique, however, the additional requirement must be met that the infiltrant and tungsten should be mutually insoluble either below or above the melting point of the infiltrant. Moreover, the infiltrant should act not only as a "filler" but also as a *lubricant* during the machining operation, this combined action preventing the tearing out of particles as well as burnishing and high tool wear which would otherwise occur.

Gold, copper and alloys of the two in all proportions appear to conform best to the above requirements. The cost factor should not prevent the use of gold, since the latter when removed by volatilization can be recovered. Silver, on the contrary, is not a very satisfactory infiltrating material in our case since tungsten shows a slight solubility in molten silver. The reprecipitation of tungsten onto the larger grains which takes place upon cooling changes somewhat the value and the character of the porosity attained during the initial sintering operation.

When using copper, the impregnation is carried out at about 1350 °C [6]), for a period of not less than 10 minutes in the case of ingots $^3/_8'' \times ^3/_8''$; larger ingots require a longer impregnating time. It is important to "fill" the ingot completely: if a small portion of it is not properly infiltrated, breakage of the tungsten or of the tool may result. In order to ensure proper filling, the ingot is placed on top of a weighed amount of copper (OFHC), slightly in excess of the amount which will be necessary; the weighed amount will be 8-10 % of the weight of the tungsten when the porosity is 83-84%. The infiltration is carried out in a hydrogen atmosphere and the temperature is first slowly raised to a point below the melting point of the impregnant and held there a few minutes to permit the interior of the ingot to attain the same temperature as the surface. When the temperature is finally raised to 1350 °C the molten copper will penetrate the tungsten body from the bottom by capillary action, this process being facilitated by the fluxing action of the hydrogen.

No tungsten grains can be detected under microscopic examination of a freshly machined surface, since a thin copper film has been smeared over the entire area. If the copper film is chemically removed from the machined surface, the smoothness and flatness of the grains indicate that they have actually been cut by the tool and not merely torn out.

[6]) All temperatures indicated for our process are brightness temperatures measured by sighting on the tungsten.

The volatilization of the copper is effected by heating the machined parts in a vacuum furnace at 1800-1900 °C for a sufficient time. The resulting parts under spectroscopic examination show only an extremely faint trace of copper. In order that the machined parts will retain dimensional stability and proper porosity during the volatilization (*fig. 2*), it is essential that the sintering of the tungsten frame prior to the infiltration was conducted for a sufficient length of time at a temperature considerably higher than that necessary for the subsequent evaporation of the copper (and, of course, higher than the temperatures at which the parts will further be treated or used). Since the proper sintering temperature depends to a large extent on the characteristics of the tungsten powder, on the pressure used in forming the bars and on the sintering atmosphere (e.g. its water vapour content), all these factors have to be carefully selected. An example of the technique as developed for the dispenser cathodes [5]), is the following. Tungsten powder

Fig. 2. Photomicrograph showing a polished section of the tungsten surface after the volatilization of the copper. The average pore size is of the order of a few microns, the pore separation varying between a few microns and a few tens of microns. (Such small pore distances are desirable for the surface of dispenser cathodes [7]).)

[7]) This will be shown in a forthcoming publication by E. S. Rittner and R. H. Ahlert of the Irvington Laboratories.

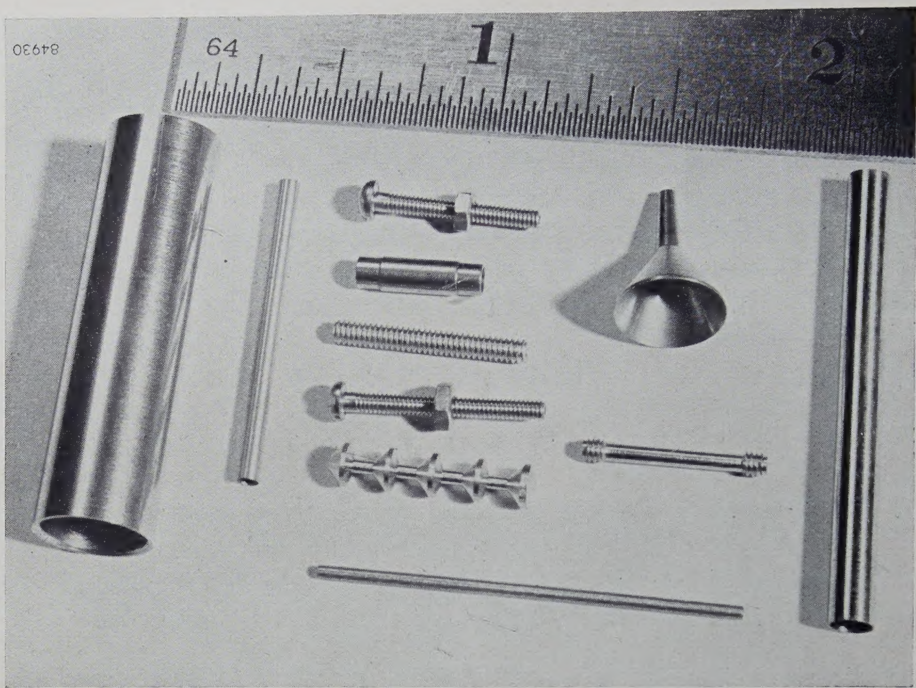

Fig. 3. A number of tungsten parts made by the new technique.

with the characteristics shown in *Table I* is pressed into bars at 2000 kg/cm². After pre-sintering for 20 minutes at 1150 °C, the ingots are sintered for 20 minutes more at 2400 °C in a water-free reducing atmosphere (cracked anhydrous ammonia). The density of the ingot then reaches a value of 83-84% of the solid tungsten value.

Normal machining operations on the infiltrated ingots can be carried out with relative ease at densities up to about this value. Increases in density above this value will make the machining progressively more difficult because of a rapid increase in the percentage of non-connecting pores which cannot be infiltrated. This will actually limit the application of the technique described to tungsten parts of density slightly less than 90%.

Table I. Grain size distribution of tungsten powder which in the case described as an example was used for machining parts of 83% density. The distribution is determined by a standardized elutriation analysis, passing an elutrient (water) over the powder sample a through and number of widening vessels, in which fractions of the powder are deposited. In the first, narrow vessels, where flow is rapid, chiefly large grains are deposited; smaller particles settle in the subsequent, wider vessels.

Fraction No.	% settled	Equivalent particle radius
1	29	> 6 μ
2	25	
3	11	
4	13	
5	22	< 2 μ

Another check on the powder characteristics is obtained from the Scott test, in which the density of the powder is measured after shaking for some time in a vessel. In our case this Scott density is about 68.4 gram/cubic inch (4.1 g/cm³).

It has been mentioned that the application to dispenser cathodes depends on the very porosity of the tungsten (a high percentage of the pores must also interconnect in this case). A number of other applications of tungsten may be conceived for which the porosity of the metal does not matter, while the ease of making intricate forms (see *fig. 3*), the smoothness of the surface and the close dimensional tolerances achievable by the new technique are of importance. An additional asset of this technique is that it allows fabrication of extremely fine parts which — even when disregarding tolerances etc. — could not previously be made either by pressing in a die or by machining a pre-sintered ingot, because of the inherent weakness of the material in this stage.

Summary. Pure tungsten metal obtained by the well-known sintering process is extremely hard and brittle at normal temperatures, so that machining possibilities are very limited. It has been found that porous tungsten, of density up to 90% of the value for solid tungsten, can be accurately machined by normal methods and at normal temperatures when the tungsten body is infiltrated with suitable metals, such as copper or gold. After machining, the filling metal, which also acts as a lubricant, is removed by evaporation. No shrinkage or warping of the machined parts is to be feared provided that the tungsten ingot prior to machining was sintered to the required degree at a temperature higher than that to which the tungsten part is subjected during evaporation of the filler or in subsequent use. Intricate parts of different sizes, including very small ones, can be made in this way to close dimensional tolerances.